NAVAL FACILITIES ENGINEERING SERVICE CENTER
Port Hueneme, California 93043-4370

TECHNICAL REPORT

TR-2055-SHR

ECONOMIC ANALYSIS PROCEDURE FOR EARTHQUAKE HAZARD MITIGATION

by

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February 1 997

Report Documentation Page

Report Date	Report Type	Dates Covered (from... to)
01FEB1997	N/A	-

Title and Subtitle Economic Analysis Procedure for Earthquake Hazard Mitigation	**Contract Number**
	Grant Number
	Program Element Number
Author(s) J. M. Ferritto	**Project Number**
	Task Number
	Work Unit Number
Performing Organization Name(s) and Address(es) Naval Facilities Eng Service Center, Port Hueneme, CA 93043-4370	**Performing Organization Report Number** TR-2055-SHR
Sponsoring/Monitoring Agency Name(s) and Address(es)	**Sponsor/Monitor's Acronym(s)**
	Sponsor/Monitor's Report Number(s)

Distribution/Availability Statement
Approved for public release, distribution unlimited

Supplementary Notes

Abstract
The 1990s represents a period in which both government and industry are attempting to reduce expenditures, focusing on economics of operation as a priority problem. Both are undergoing a downsizing to eliminate unnecessary functions and personnel with an increased emphasis on cost effectiveness and maximization of return on investment. All construction has a purpose and the economics of use is involved in the decision process to build or upgrade. Commercial and industrial construction are categories of investment which generally are designed to serve in an income producing role. The user commits to the expenditure of an amount of resources to establish an operating environment to meet a specific objective. In the corporate world, the objective may be an office complex designed for administrative or sales functions, or the objective may be an industrial complex designed to produce a product. It may be a hospital designed to assist the community by offering medical services. In the government sector, the objective might be an office complex to administer a state or federal program. In the Department of Defense, small self-contained cities are operated to meet the military needs for ports, airfields, industrial facilities, administration and personnel housing. Executive Order 12911 directs a screening program to quantify the numbers of federal buildings requiring seismic upgrade and an estimate of the cost to bring these deficient buildings up to current requirements. The expected costs of upgrade are huge and economics plays a central role in the decision process.

Subject Terms

Report Classification unclassified	**Classification of this page** unclassified

Classification of Abstract	Limitation of Abstract
unclassified	SAR
Number of Pages	
44	

Executive Summary

While previous research by others has dealt with the subject of economics of seismic design, none has provided a framework to examine a single building in detail; that is why this report has been written. There is an increased emphasis on post-earthquake building functionality by the engineering community. In this light, it is essential to be able to evaluate the extent and location of expected building damage. Are there any weak links in the building system design which will preclude operability? Operability demands that the building be viewed as a total system not just a structural system. Utilities and the other elements must function to have operability. We need to know what building system elements are damaged in addition to the damage to the lateral force resisting system. This report presents a detailed analysis procedure which can evaluate the economics of seismic design for a building system.

The purpose of this analysis procedure is to perform an economic comparison of alternative designs of a structure considering initial construction expenditures and expected earthquake induced damage over the life of the structure. It may compare different types of construction or different design levels. It is thus intended to assist the user and the design engineer in obtaining cost effective seismic construction. The Navy seismic economic analysis procedure is a process of estimating earthquake damage based on both interstory drift (displacement) and floor acceleration. As such it recognizes that the building system is composed of components, some structural, some nonstructural and some mechanical and electrical, which are affected by displacement or drift. It also recognizes that damage is induced in some building system components which are mounted to floors or ceilings by the transmitted story accelerations. The procedure of including both drift and acceleration is a significant factor in this procedure which is an improvement over other techniques which focused only on drift. Failure to include the acceleration induced damage leads to erroneous conclusions that mere stiffening which reduces drift is fully effective. For every dollar that is invested in stiffening a structure, a portion of it may be wasted because stiffening results in increased floor accelerations which can cause additional damage to acceleration sensitive components like contents.

This report defines the steps in the procedure for conducting an economic analysis. The initial step is to establish the seismic exposure of the building site. The building is divided into components based on function and damage mechanism Some components are drift sensitive while others are acceleration/force sensitive. The cost of building components must be identified to distinguish variations in cost of alternatives. A series of analyses are conducted for the range of expected site ground motion for each alternative concept to determine interstory drift and floor acceleration. Damage functions are presented in the report to determine component damage. Since the damage can occur at any time over the life of the structure, the present value of the damage cost is determined. Loss-of-use costs may be included. Damage costs are combined with initial strengthening costs to determine total expected cost for comparison of alternatives.

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Introduction

The 1990's represents a period in which both government and industry are attempting to reduce expenditures, focusing on economics of operation as a priority problem. Both are undergoing a downsizing to eliminate unnecessary functions and personnel with an increased emphasis on cost effectiveness and maximization of return on investment. All construction has a purpose and the economics of use is involved in the decision process to build or upgrade. Commercial and industrial construction are categories of investment which generally are designed to serve in an income producing role. The user commits to the expenditure of an amount of resources to establish an operating environment to meet a specific objective. In the corporate world, the objective may be an office complex designed for administrative or sales functions, or the objective may be an industrial complex designed to produce a product. It may be a hospital designed to assist the community by offering medical services. In the government sector, the objective might be an office complex to administer a state or federal program. In the Department of Defense, small self-contained cities are operated to meet the military needs for ports, airfields, industrial facilities, administration and personnel housing. Executive Order 12911 directs a screening program to quantify the numbers of federal buildings requiring seismic upgrade and an estimate of the cost to bring these deficient buildings up to current requirements. The expected costs of upgrade are huge and economics plays a central role in the decision process.

In the 1980's the Naval Civil Engineering Laboratory, now named the Naval Facilities Engineering Service Center, developed a procedure for the economic analysis of seismic design levels and lateral force resisting systems, Ferritto (1982, 1983, 1984a and 1984b). That work lead to the development of Chapter 7 of NAVFAC P355.2, Seismic Design Guidelines For Upgrading Existing Buildings. The procedures have been adopted for use by the engineering community and used to analyze the seismic upgrade of several hospitals. Recently the State of California passed SB920 which mandates an economic analysis be conducted when new earthquake hazard mitigation technology such as base isolation or viscoelastic dampers are proposed for use in State construction projects. The State of California has adopted for use the economic analysis procedures developed by the Navy referenced above. New data on damage was added. The State of California procedures for conducting an economic analysis are contained in "Earthquake Hazard Mitigation Technology Guidelines", Way (1995). This report will present the standardized procedure and the new damage data.

Economic analysis techniques have been used extensively in business and engineering. There has been investigation of the cost of seismic construction upgrading in a number of documents such as FEMA 157 (1988). FEMA 228 (1992) and 229 (1992) discuss a benefits-cost model for the rehabilitation of buildings. A significant study was performed by the Applied Technology Council, ATC-13 (1985). These studies took a macroeconomics perspective looking at the decision process for large inventories of buildings, expressing costs on a per square foot basis, and developing guidelines for application to classes of construction. The models for estimating cost and damage focused only on evaluating the lateral force resisting system. Harris and Harmon (1986) performed an economic analysis using techniques very similar to those outlined in Ferritto (1984a), but the work was unfortunately oversimplified to the point where its results are limited. They related damage only to drift and failed to include story force/acceleration as a separate damage mechanism. Ductility demand alone can not represent all damage since direct force/acceleration effects on elements mounted to floors or ceilings and damage to building contents would not be included. One would erroneously conclude that simply stiffening a building would reduce all damage when in effect we find that induced floor accelerations are increased by stiffening. One would never be able to completely assess the cost - benefits of base isolation if acceleration damage were omitted. Their damage function for the total building consisted of interpolating between yield and collapse ductility levels for only the lateral force resisting element neglecting the possibilities of different level of damage to the other building elements and subsystems.

While previous papers have dealt with the subject of economics of seismic design, none has provided a framework to examine a single building in detail which is why this report has been written. There is an increased emphasis on post-earthquake building functionality by the engineering community. In this light, it is essential to be able to evaluate the extent and location of expected building damage. Are there any weak links in the building system design which will preclude operability? Operability demands that the building be viewed as a total system not just a structural system. Utilities and the other elements must function to have operability. We need to know what other building system elements are damaged in addition to the damage to the lateral force resisting system. This report presents a detailed analysis procedure which can evaluate the economics of seismic design for a building system.

The purpose of this analysis procedure is to perform an economic comparison of alternative designs of a structure considering initial construction expenditures and expected earthquake induced damage over the life of the structure. It may compare different types of construction or different design levels. It is thus intended to assist the user and the design engineer in obtaining cost effective seismic construction. The Navy seismic economic analysis procedure referenced above is a process of estimating earthquake damage based on both interstory drift (displacement) and story acceleration. As such it recognizes that the building system is composed of components, some structural, some nonstructural and some mechanical and electrical, which are affected by displacement or drift. It also recognizes the damage induced in some building system components which are mounted to floors or ceilings are damaged by the transmitted story accelerations. The procedure of including both drift and acceleration is a significant factor in this procedure which is an improvement over other techniques which focused only on drift. As noted above, failure to include the acceleration induced damage leads to erroneous conclusions that mere stiffening which reduces drift is fully effective. For every dollar that is invested in stiffening a structure, a portion of it may be wasted because stiffening results in increased floor accelerations which can cause additional damage to acceleration sensitive components like contents.

This Navy technique utilized available structural data correlating structural component member damage to measured drift levels. Additional data relating acceleration sensitive components to damage was compiled. The technique referenced above used available data at the time of its writing; since then the Loma Prieta earthquake of 1989 and the Northridge earthquake of 1994 coupled with extensive university testing have greatly increased the damage data base. In the process of developing the State of California guideline, the original damage estimation tables were updated to include the new data. This new data base is now available and was used to update damage relationships, Way (1995). The procedure for conducting an economic analysis is applicable to both new and existing structures. The procedure is appropriate for larger projects which can justify a site seismicity study and the additional steps involved. The procedure is not meant for structures where the building code is design is adequate, but rather for those structures where post-earthquake performance is under consideration. It is best applied during the design process when cost estimates of the proposed structure are usually made and the performance of the structure analyzed. When only relative performance of alternatives is required, the general procedure may be shortened as will be described in following sections.

Seismic Exposure (Step 1)

Fundamental to evaluating the potential for seismic damage is quantifying of the hazard exposure. This is accomplished by a site seismicity study which determines the intensity and characteristics of ground motion shaking which pose a risk to a specific location. The method of performing a site seismicity study has become standard practice and is used by many geotechnical firms. In general, an historical epicenter data base is used in conjunction with available geologic data to compute the probability distribution of site ground motion. The process of quantifying the level of hazard involves building a mathematical model of the region. The controlling elements of seismic source characterization depend on the tectonic environment. In the Western United States, the tectonic environment is such that earthquakes are associated with known faults. However, in the Eastern United States, the causative geologic structures are generally not as well defined. The seismic model must be based on the knowledge of the local area in sufficient detail to yield results appropriate to estimate site motion for events with return times on the order of 1,000 years. The results of a seismicity study are presented in an engineering report which gives a discussion of the results, the site acceleration probability distribution, and the determination of specific site acceleration levels to be used for building design. Figure 1 illustrates a typical non-exceedance probability ground acceleration distribution for a site for a given exposure period. The word “total” is used because it represents the combined effects of all seismic source zones acting on the site. A histogram can be constructed showing the expected probabilities of various levels of ground shaking, Figure 2. Development of Figures 1 and 2 are the first steps in the economic analysis and are usually part of a routine seismicity study for a large facility.

The structural design engineer may use either a response spectra or earthquake time history in the analysis of a structure. The data base of available recorded accelerograms is routinely used to generate a series of spectra or time histories for use by the structural and geotechnical engineers in further assessment of the site.

Seismic Cost of Alternatives (Step 2)

The economic analysis may be applied to new construction to evaluate:

- alternative structural systems such as moment frame vs. braced frame or shear wall
- alternative materials, concrete vs. steel
- alternative concepts such as conventional construction vs. new earthquake hazard mitigation technology such as base isolation
- alternative seismic design load levels such as various acceleration levels
- alternative earthquake return time design levels

For existing construction, economic analysis may be applied to evaluate:

- alternative seismic upgrade levels
- alternative concepts of upgrade including conventional construction vs. new earthquake hazard mitigation methods

When an economic analysis is applied to a design project considering alternative concepts, it is necessary to evaluate the cost of each alternative. A preliminary structural design must be performed to determine structural member sizes for each alternative. Additionally nonstructural items affected by the seismic forces must be designed to the extent that they represent significant cost factors which vary among the alternatives. For special structures such as base isolated buildings, special requirements such as building clearance, flexible utility connections, isolator design, etc. must be included to be able to define the structure. Once the structure is defined a detailed cost estimate can be completed. This is a very important step in the economic analysis and one which determines the level of accuracy. As is usual practice in preparing a cost estimate, the structure should be broken down into major components and the cost of each component noted separately. The division of the building into components is an important step since each component will be later analyzed for damage. As will be shown later, it is important to separate out components which are drift sensitive from those that are force/acceleration sensitive. Equipment mounted on floors will be sensitive to the acceleration levels it receives; while, items such as vertical plumbing risers spanning between floors will be drift sensitive. Some items will fall into both categories. As a minimum, the major components should include the structural system, non structural partitions, exterior walls, floors, foundations, ceiling lights and fixtures, mechanical equipment, electrical equipment, and building contents. Where desired, a component may be subdivided into elements for a more detailed evaluation. It is required that a detailed cost estimate be compiled for each alternative being evaluated. There may significant portions of the cost estimate which do not vary among the alternatives. The amount of work involved is not as great as it might appear. Once a routine detailed cost estimate is prepared for the basic structure concept, as is standard practice, only those elements which change among alternatives need be evaluated. Use of individual components has the added benefit of showing where the damage occurs and whether there are any weak links in the building system. This is especially important for buildings which are expected to remain operational after an earthquake.

To illustrate the process, a study was performed in which a 185-foot square three-story building was designed for various steel and concrete lateral force resisting alternatives. Five lateral force resisting alternatives were evaluated for six design acceleration levels. Figure 3 shows the cost increase of seismic design as a function of the design acceleration level for the various alternative lateral force resisting systems. For this illustration, the structure was designed to be at the elastic limit at the design acceleration level to facilitate comparison. It is interesting to note that in this case, the cost of seismic strengthening is a relatively minor part of the structure's total cost.

Damage Evaluation (Step 3)

Earthquake induced structural damage is caused principally by two mechanisms: interstory drift and story forces/accelerations. Drift is the mechanism usually causing damage to structural systems. There have been numerous tests conducted of lateral structural resisting systems which show the strength of these elements under cyclic load reversal. Building elements anchored to floors or suspended from ceilings feel the floor acceleration and respond as substructures. Depending upon the natural period of the structure, floor accelerations can be significantly higher than surface ground motion levels and tend to increase with height within the structure. The original Navy work, Ferritto (1984a), presented data tables relating damage of various components to drift and to acceleration. Way (1995) has updated this information based on experience over the last decade. Figure 4 gives the most current damage estimate data.

For each alternative it is necessary to conduct a series of dynamic analyses to compute damage over a range of possible ground motion levels. Looking at the histogram in Figure 2, it can be seen that the bins cover increments of 0.1 g from a range of 0 to 1.0 g for the particular site. A set of ten dynamic analyses starting at 0.05g to 0.95g would be appropriate for this case to cover the range of possible accelerations which could produce expected damage of significance. For a specific alternative, a basic finite element model would be constructed; then, the ten analyses of the model would be performed in which the applied load level was increased from 0.05 g to 0.95g. The author has found that performing a nonlinear time history analyses using programs like the DRAIN2DX/DRAIN3DX computer program to be highly efficient. The amount of effort involved is not increased significantly beyond the basic analysis since repeated analyses at different load levels only involve adjusting a few parameters to change or scale the acceleration load record and the structure damping level. The topic of damping will be discussed below. No changes need be made to the structure geometry model. The results of the analysis are used to establish the interstory drifts and floor accelerations at each applied load increment. These are used to compute the damage ratio for each component by using Figure 4, examining the individual component elements and their appropriate drift and/or floor acceleration. The damage evaluation process is repeated for each of the ten applied load levels from 0.05g to 0.95g for each alternative. This part of the analysis can be automated by a program which post-processes the output from the finite element program and computes damage to all components and then sums component damage for overall building damage at that level of applied loading. Thus to summarize:

Alternatives 1... i

Acceleration Increments 1... j

For each dynamic analysis for a given alternative, i, and applied load level, j, each of the identified components such as structural frame, mechanical equipment etc. is evaluated for damage using the drift and floor acceleration response data

The element damage relationship expressed in Figure 4 is in terms of a damage ratio; the actual element damage cost is obtained by multiplying the damage ratio from Figure 4 times the element cost from the cost estimate. Alternatively the element damage can be summed to a component level based on average damage ratios and then expressed as a component damage cost based on the average damage ratio times the component cost. Experience has shown that the cost of repair is greater than the original cost because elements must first be removed before the damaged component can be repaired or replaced. A component repair multiplier, R, is used to account for this increase. The repair multipliers are based on GSA data obtained from actual experience. For example, when a lateral force element is damaged the level of damage is first computed from the drift data. This level of damage is then multiplied by 1.5 to take into account that the repair process requires more work than the initial installation. Specifically, a given level of drift may represent 10 percent damage to the element which would become 15 percent of the dollar cost of the element (10% times 1.5). The following repair multipliers are suggested to increase the component costs:

Lateral force resisting system	1.5
Other structural components	1.5
Mechanical equipment	1.25
Electrical equipment	1.25
Architectural elements	1.25
Elevators	1.25
Contents	1.05

The Total Building Damage for a given iteration of acceleration load level can be expressed as:

$$\text{Total Building Damage} = \Sigma \text{ (Damage Ratio) * (Component Cost)* (Component Repair Multiplier)}$$

Additional cost factors can be included in the Total Building Damage at this point, such as loss of life, injury and down time. Loss of functionality can be a very significant cost factor for certain types of facilities. It can be estimated in terms of lost revenue for income producing facilities or in terms of the work-force salaries for service facilities. The owner/user is willing to pay an aggregate salary to have a work-force perform a set of functions. The inclusion of these indirect costs are significant and can shape the results of an analysis. The users can in most cases express the loss of use of the structure and this information should be included.

The Expected Building Damage Cost is computed by multiplying the probability that the acceleration increment from the histogram will occur, such as Figure 2, times the damage or damage ratio for the building evaluated at that acceleration increment, and summed over all acceleration loading increments. The Expected Building Damage Cost for the specific alternative concept over the range of possible accelerations is given by:

$$\text{Expected Building Damage} = \Sigma \text{ (Total Building Damage for increment “bin” of acceleration) * (Acceleration “bin” Probability)}$$

Since the damage will occur some time in the future it must be expressed in terms of the present value (PV) to relate it to the current costs of seismic strengthening or remediation.

$$\text{Current Expected Damage Costs} = \text{PV(Expected Building Damage Cost)}$$

In most cases, we do not have data which defines the temporal sequence of expected earthquakes over the life of the structure. It may be assumed that the risk is uniform over the exposure period. The present worth can be determined by dividing the exposure time into segments and then taking the present value of each segment or more simply by using a single average exposure time equal to half the total exposure time.

The life cycle cost of this alternative is the sum of the initial construction cost plus the present value of the expected damage.

$$\text{Alternative Cost} = \text{Initial Construction Cost} + \text{PV(Expected Damage Costs)}$$

Engineers have used two forms of structural dynamic analysis: response spectra procedures and time history solutions. A nonlinear time history solution is preferred because it directly computes displacements and floor accelerations taking into account structure yielding. Since there is substantial variation among earthquake records even when scaled to the same nominal peak acceleration value, the selection of an acceleration record can be a factor in establishing the maximum response of the structure. The choice of records should be examined to quantify variation in response and a series of three acceleration time histories is typically used to cover a range of response. It is important to note that as the ratio of applied loading to design load increases, the structure undergoes increased deformation and possible nonlinear behavior. As the level of deformation increases, an increase in damping occurs which must be included in the analysis. Values for damping as a function of inelastic deformation have been discussed in the literature and are presented in Ferritto (1984a). Care must be taken at each load level iteration to select the appropriate damping for that load increment.

Illustrative Example

To illustrate the economic analysis of alternative concepts, the building discussed above will be used. The structure is a proposed three-story square building 185 feet on a side.

Problem: Consider for a new building the alternative designs of

- Steel frame and concrete shear wall
- Steel braced frame

The alternatives of frame/shear wall design and braced frame design will be compared for a 0.2g elastic design acceleration. The building is shown in plan view in Figure 5a and the two lateral force resisting alternatives are shown in Figure 5b. The components identified for analysis, their costs and repair multipliers are shown in Table 1. The components have been divided based on their susceptibility to drift or acceleration. The initial construction total costs for each alternative are

Steel Frame and Concrete Shear Wall $5876,700

Steel Braced Frame $5,928,800

For each increment in acceleration between 0.05g and 0.95g a nonlinear analysis was performed and the interstory drift and floor accelerations determined. Using drift and acceleration damage data from Figure 4, damage ratios were computed and are shown in Figure 6. The data in Figure 6 was combined with the data in Figure 2 to compute Total Building Damage. The calculations are shown in Table 2. The present worth of the future damage which can occur any time in the 50 year exposure period is determined based on the average present worth factor for increments of time using a 7 percent interest rate. The interest rate was based on the approximate rate of return on long term federal bonds and is thought appropriate for federal construction. The expected damage is:

Steel Frame and Concrete Shear Wall $206,000

Steel Braced Frame $96,000

The loss of building function from an earthquake can be a significant factor and can be included at this point. Here the user develops a value for the operation of the building in terms of the value of the product produced in the building. For administrative buildings the value of the salaries paid to the occupants can be an approximate indication of the value of the operation. As an illustration consider that the out of service lost time might be estimated as follows based on the dollar value of the damage and the time to repair:

Steel Frame and Concrete Shear Wall 10 weeks

Steel Braced Frame 5 weeks

If the building housed 200 people with a total annual payroll of $10 million, one week of lost productivity would be about $200,000 times the present value factor 0.28 or $56,000.

The total cost of the two alternatives involves summing the initial construction costs plus the present worth of the total damage and lost time costs expected. In this example they are:

Steel Frame and Concrete Shear Wall $5,876,700 + $206,000 + $560,000 = $6,642,700

Steel Braced Frame $5,928,800 + $96,000, + $280,000 = $6,304,800

Up to this point the interest rate and the life of the structure have not been discussed. Both of these can affect the life cycle cost and influence the choice of options. It is up to the building owner/user to select these values based on the value of money to him/her and the projected useful life of the structure. For federal construction the value of borrowed money such as long term Treasury Bonds is a good indication of what money is costing. Increasing the value of the interest rate makes the present value of future losses less and reduces the economic worth of damage prevention over initial savings. It becomes harder to justify seismic damage reduction technology. Conversely if borrowed money were without cost, seismic improvements would be very attractive. Buildings tend to remain in service for long periods of time. Fifty years has been used as the economic life for federal construction. Increasing the life of the structure increases its exposure to damage but also increases the time factor in present value calculations which reduces the present worth of future damage. The specifics of the problem determine the net effect. In general the life of the structure has less effect than the interest rate.

Simplification of General Approach

The above procedure involves three main steps: the quantification of the seismic hazard in probabilistic terms, the determination of the initial costs of seismic strengthening or remediation, and the determination of the expected damage. It was proposed to use an incremental approach in which the ground motion acceleration probability distribution is expressed as a histogram composed of incremental "bins" of acceleration and their associated probabilities of occurrence. This produces a full and complete analysis of the best estimate of the seismic exposure. However, a site seismicity study may not always be available. The engineer is free to substitute a set of earthquake events of design interest. This set is not a complete risk assessment but rather is a comparison of the proposed structural design alternatives under an assigned set of design load conditions. Having done this, the designer may choose to consider the average performance of the structure under the assigned set of events, or perhaps the worst case event, or perhaps the cumulative effect of all the events. Again it is important to note that this approach is not a total risk analysis but only a relative comparative performance of the alternatives under a set of design conditions. It was suggested that nonlinear time history finite element models of the structure be used to estimate drift and floor accelerations using sets of time histories. The engineer may substitute elastic response spectra techniques if he chooses as long as the results are adjusted for yielding.

Conclusion

This report has presented a procedure for economically comparing alternative seismic designs. The focus should be on the general procedure discussed and the choice of components and damage data should be adjusted for the specifics of the application. The data shown has evolved and will continue to evolve as the engineering community performs more earthquake case studies. The approach is a systematic method for estimating life cycle costs and calculating expected damage. The level of effort involved in this approach is greater than that of a single alternative design, but not enormously so. The procedure should be applied to significant structures where alternatives for design exist and the tradeoff costs are significant enough to justify the added analyses. Generally a site seismicity study is required for these structures of significance. Automated software in use at many geotechnical firms simplifies the preparation of a site study to produce the required histogram of site acceleration probability. The design of alternative must be carried to a level to identify the major cost differences. The automated nonlinear analysis is not significantly more complex that response spectra techniques in current use. The requirement for repeated analysis at increasing load levels requires that only minor changes be made to the input data files for the structural model. Most of the analysis can be automated.

Acknowledgment

The data in Figure 4 is based on the work of Mr. Douglas Way, Base Isolation Consultants, Inc. His work has added significantly to the methodology presented herein and is acknowledged.

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Table 1 Component costs.

Drift Sensitive Components

Component	Cost ($)	Repair Multiplier
1. Alternatives		
a. Braced frame	126,800	2.0
b. Shear walls	107,000	2.0
2. Nonseismic structural frame	625,500	1.5
3. Masonry	417,600	2.0
4. Windows and frames	120,600	1.5
5. Partitions, architectural elements	276,200	1.25
6. Floor	301,200	1.5
7. Foundation	412,100	1.5
8. Building equipment and plumbing	731,600	1.25
9. Contents	500,000	1.05

Acceleration Sensitive Components

Component	Cost ($)	Repair Multiplier
1. Alternatives		
a. Braced frame	126,800	2.0
b. Shear walls	107,000	2.0
2. Floor and roof	301,200	1.5
3. Ceiling and lights	288,500	1.25
4. Building equipment and plumbing	731,600	1.25
5. Elevators	57,000	1.5
6. Foundation	412,100	1.5
7. Contents	500,000	1.05

Total cost shear wall alternative $5,876,700

Total cost braced frame alternative $5,928,800

Table 2. Damage Ratio and present value calculation

		Braced Frame		Frame & Shear Wall	
Acceleration Increment (g's)	(1) Probability	(2) Damage Ratio Braced Frame	(1) x (2) Probable Damage Ratio	(3) Damage Ratio Shear Wall	(1) x (3) Probable Damage Ratio
0-.1	0.34	0.03	0.0102	0.015	0.0051
.1-.2	0.35	0.11	0.0385	0.05	0.0175
.2-.3	0.16	0.175	0.028	0.08	0.0128
.3-.4	0.07	0.25	0.0175	0.11	0.0077
.4-.5	0.02	0.305	0.0061	0.14	0.0028
.5-.6	0.02	0.335	0.0067	0.17	0.0034
.6-.7	0.01	0.365	0.00365	0.19	0.0019
.7-.8	0.01	0.41	0.0041	0.22	0.0022
.8-.9	0.01	0.45	0.0045	0.24	0.0024
.9-1.0	0.01	0.485	0.00485	0.26	0.0026
Total Damage Ratio		BF =	0.1241	SW =	0.0584

For 50 years of equal exposure the average Present Worth factor is 0.28

The present value of the damage costs are:

Braced Frame 0.28 * 0.1241 * $ 5,928,800 = $206,000

Shear Wall 0.28 * 0.0584 * $ 5,876,700 = $96,000

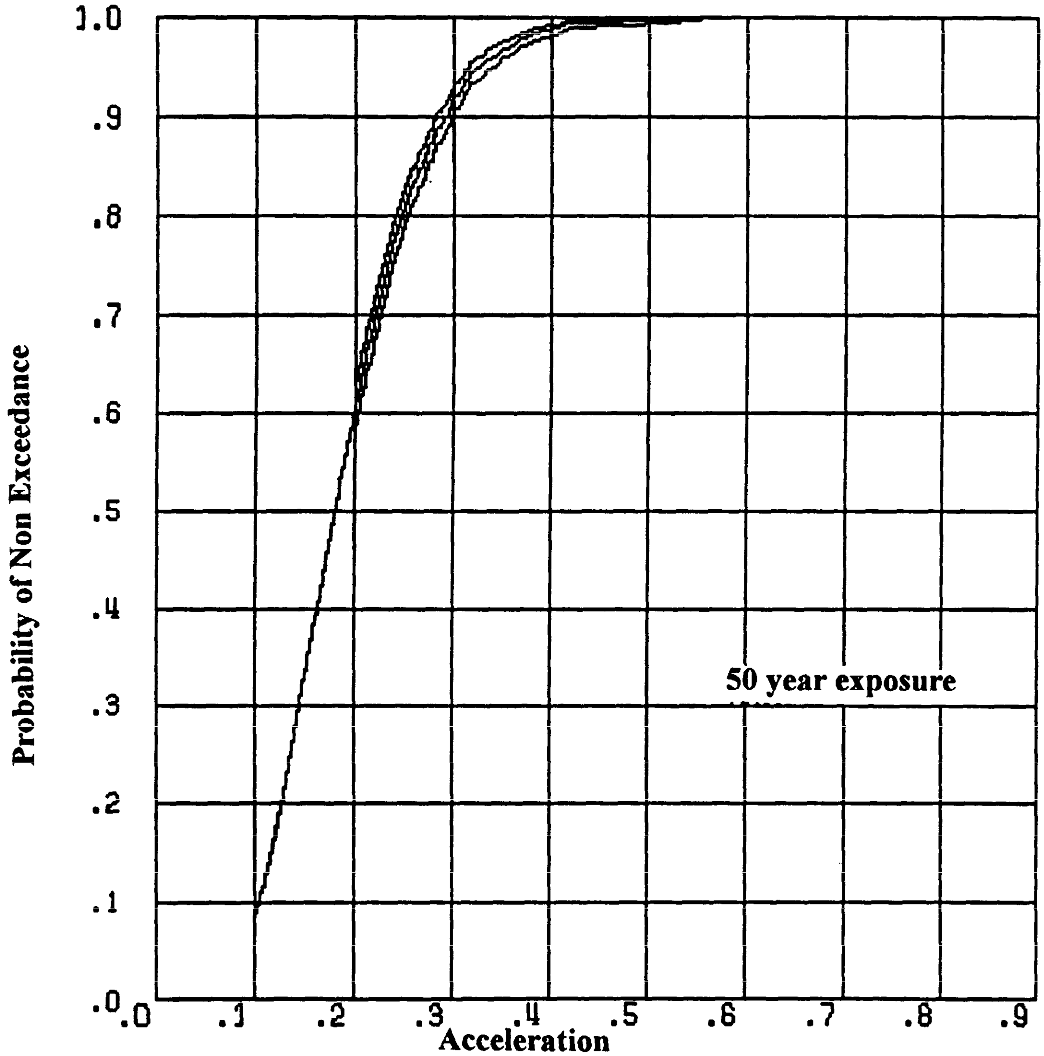
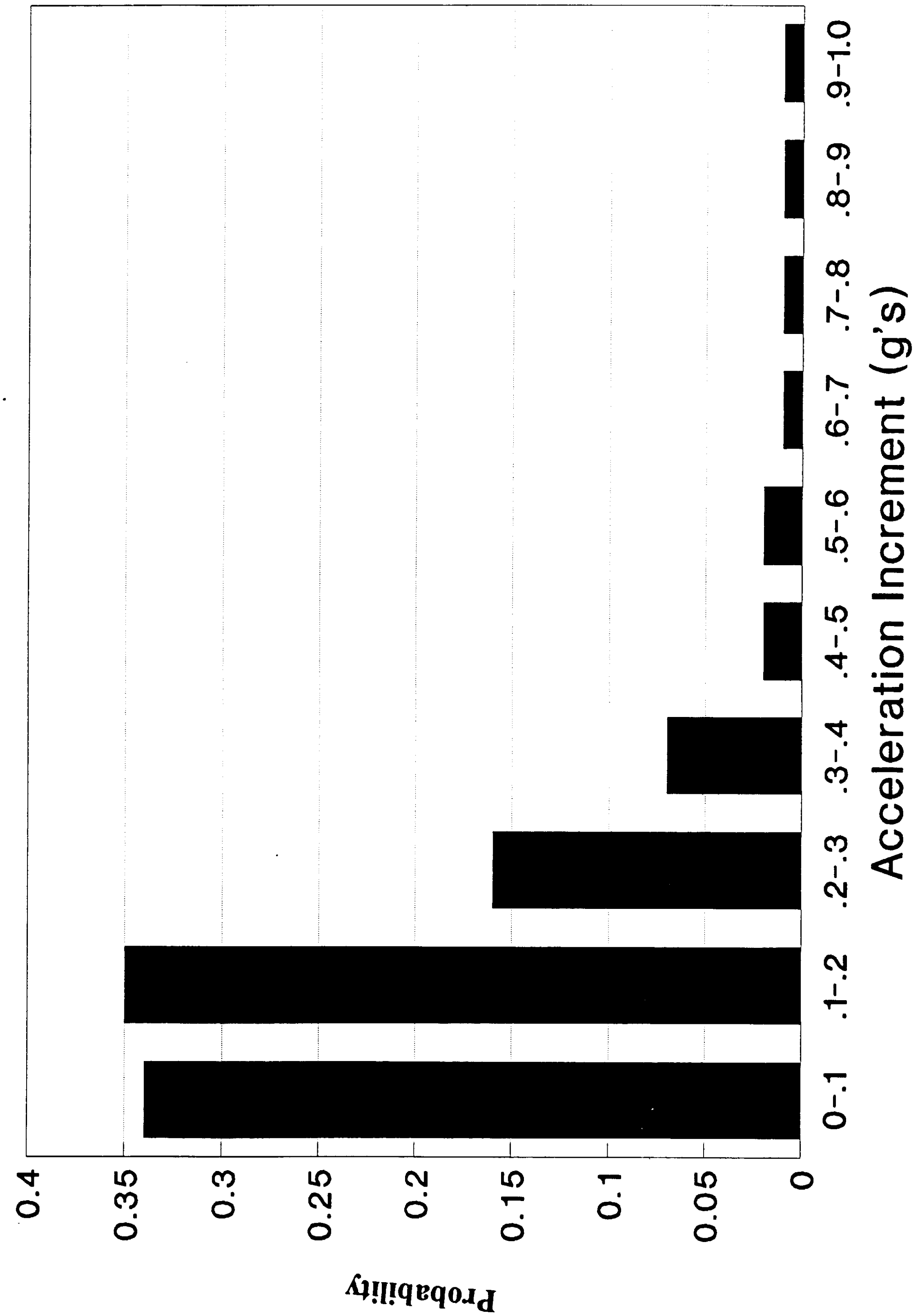


Figure 1. Total probability of non-exceedance of site acceleration.

Figure 2. Incremental acceleration level



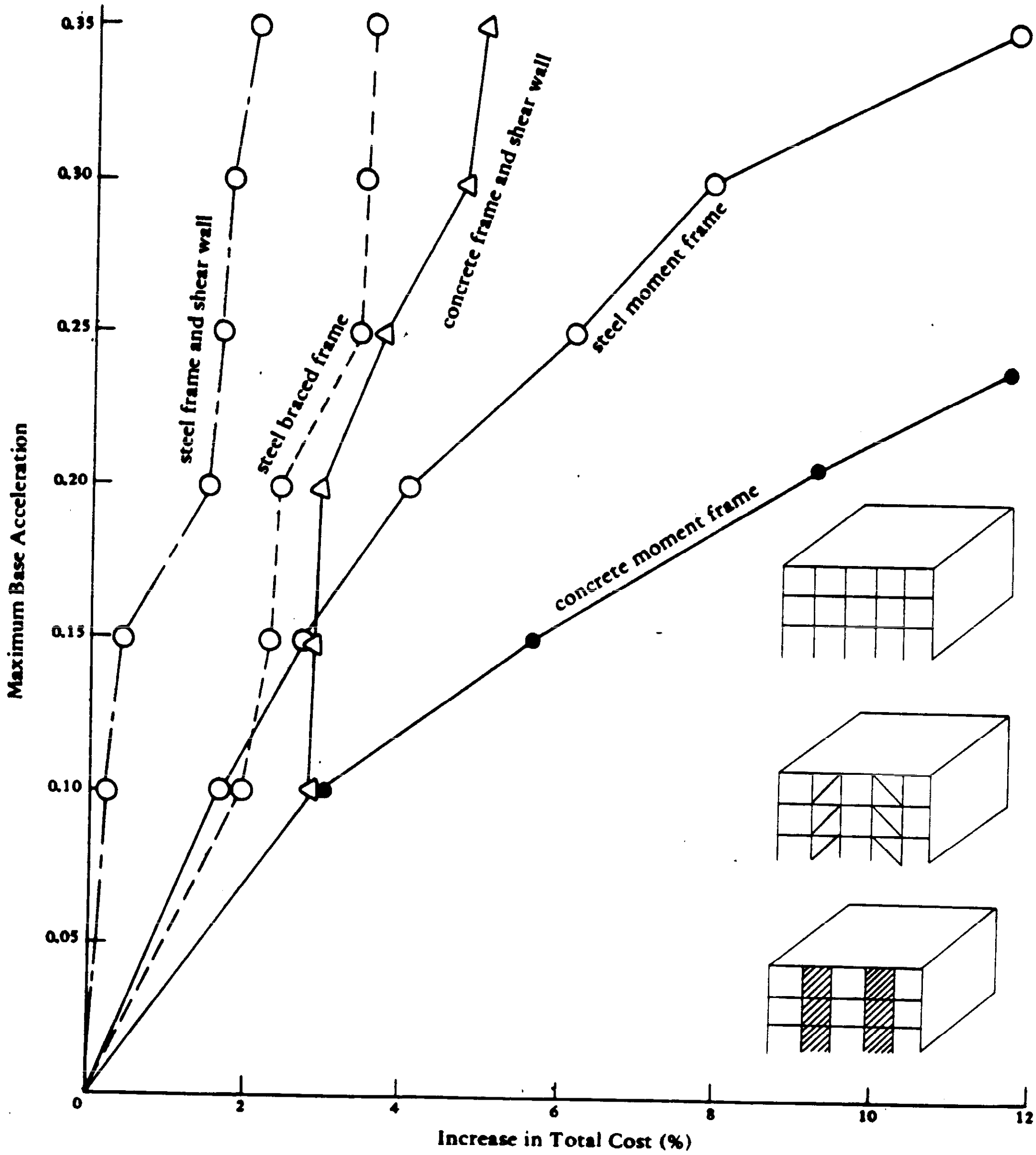
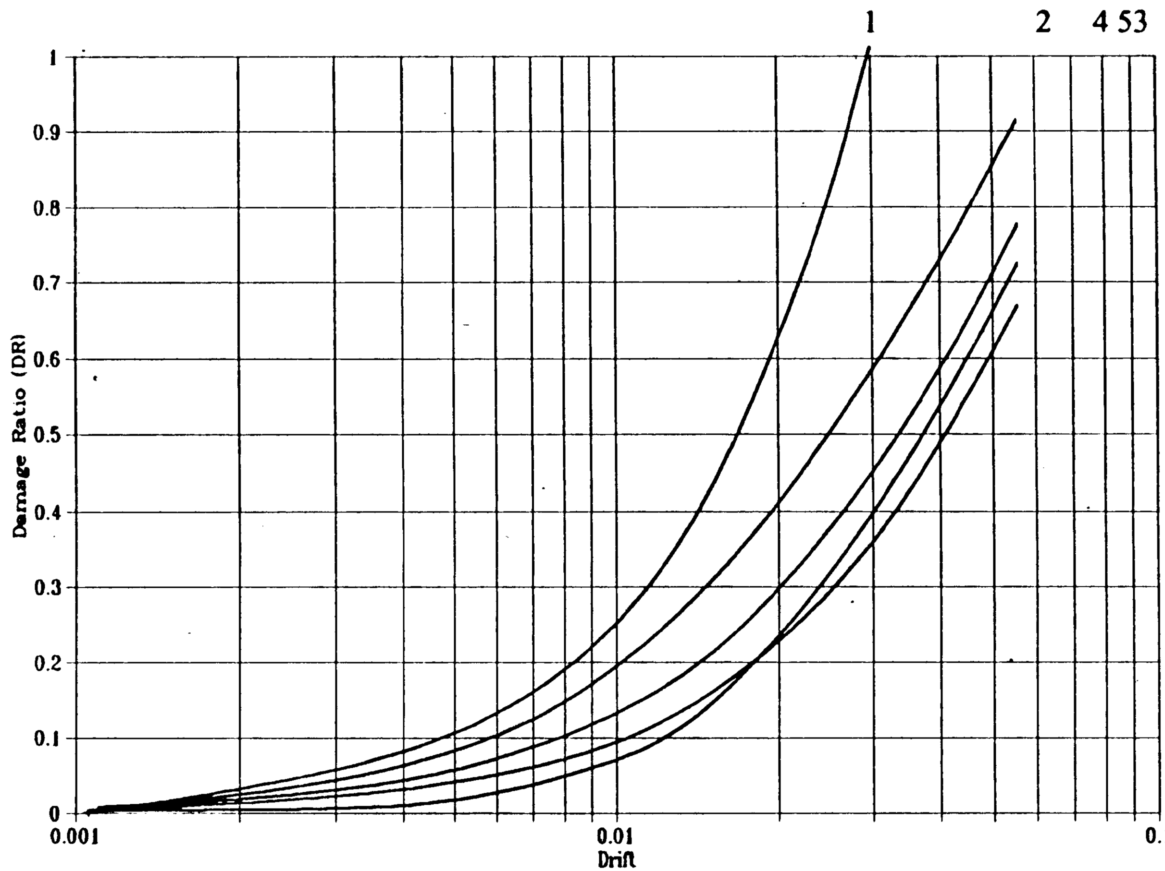
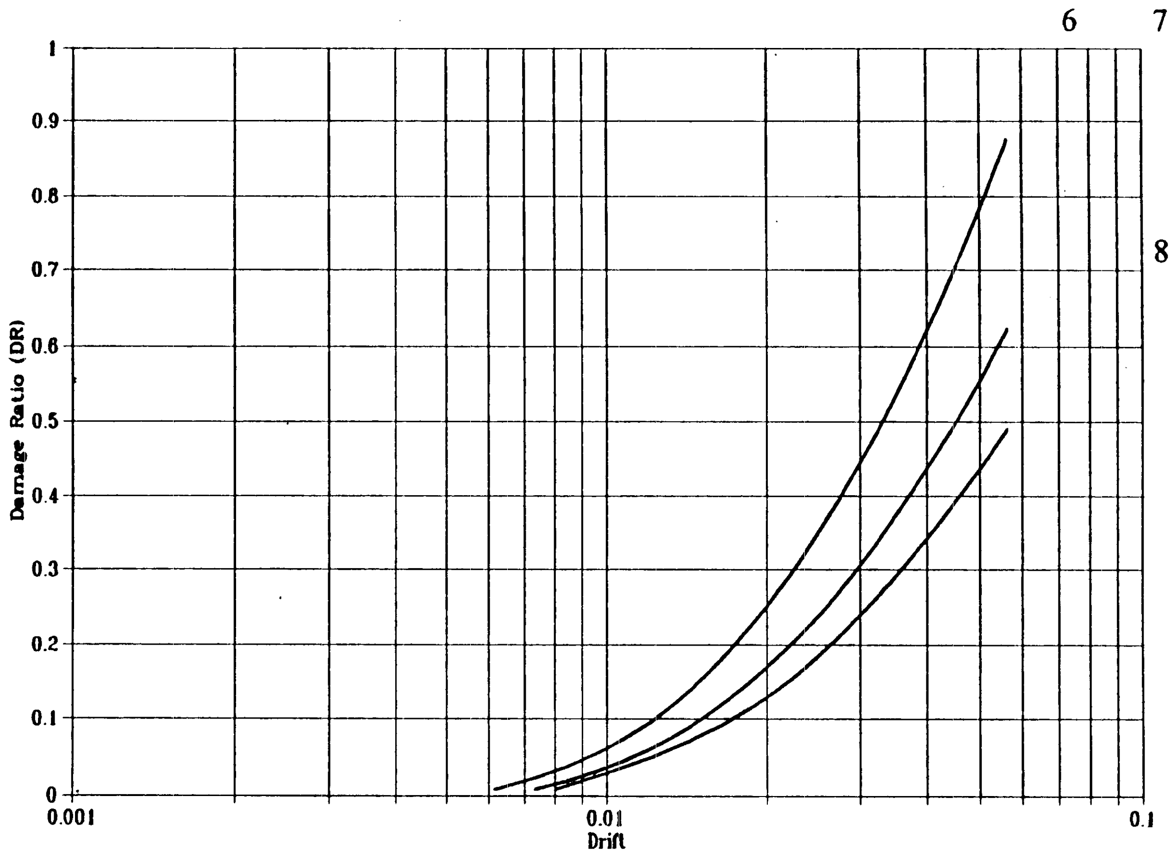


Figure 3. Cost of seismic resistance alternatives in new construction.



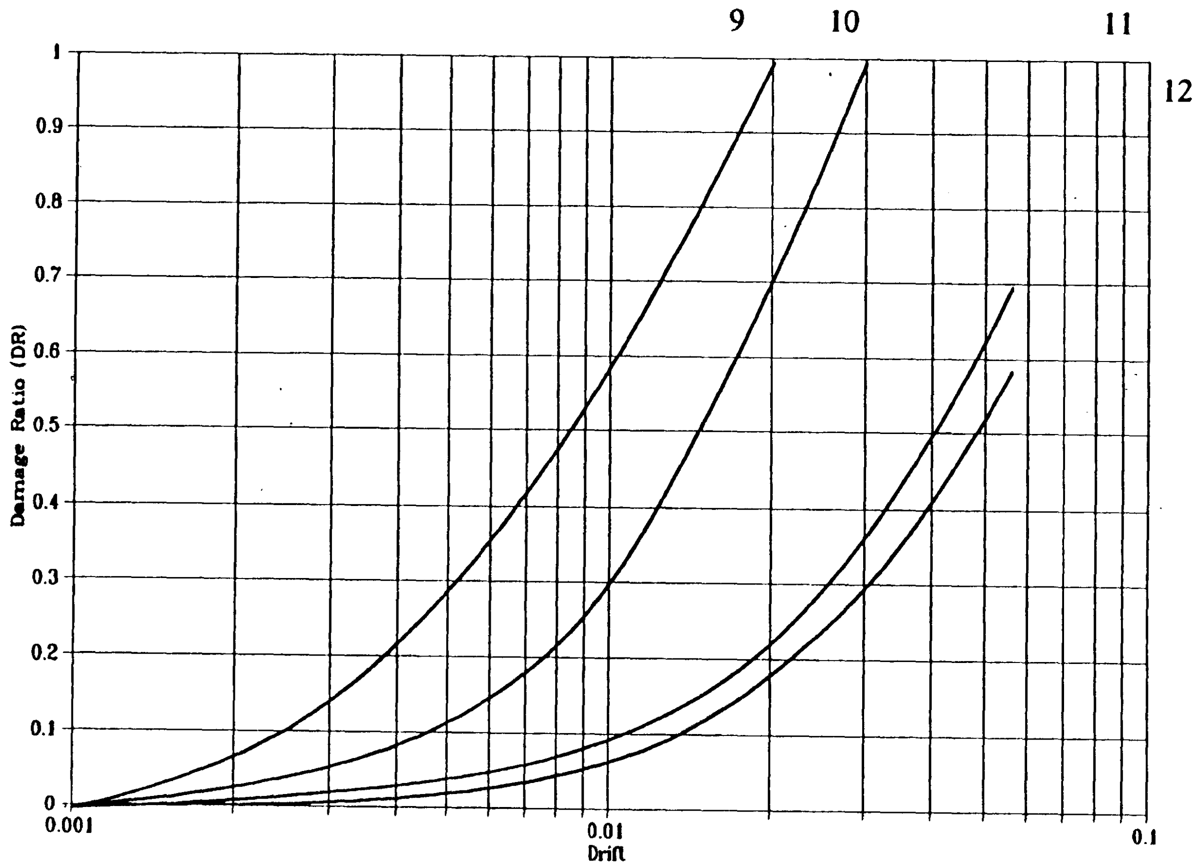
1. Masonry Walls
2. Concrete Shear Walls
3. Concrete Moment Frames
4. Steel Braced Frames
5. Steel Moment Frames

Figure 4. Damage as a function of drift and acceleration. (based on Way (1995))



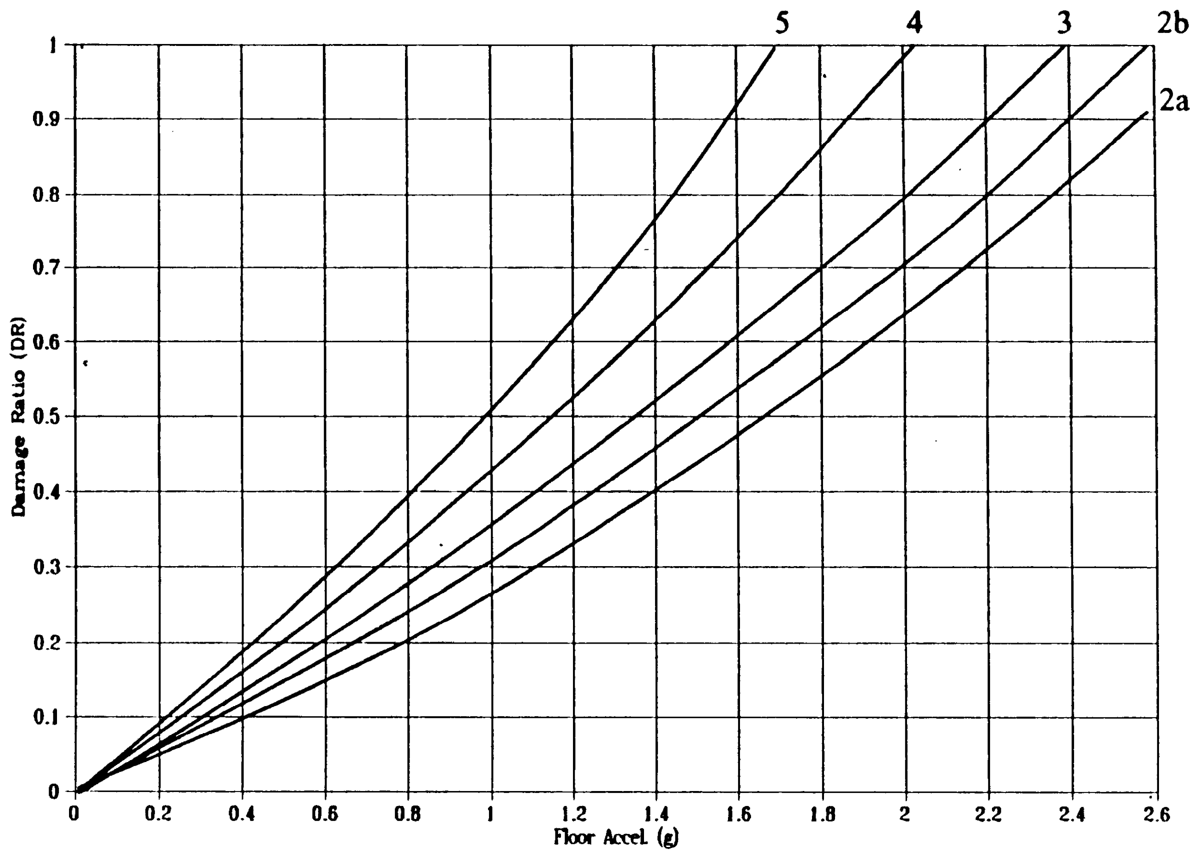
6. Structural Frames
7. Structural Floors
8. Foundations

Figure 4. Continued.



9. Architectural Glass
10. Partitions and Ceilings
11. Mechanical and Electrical
12. Contents

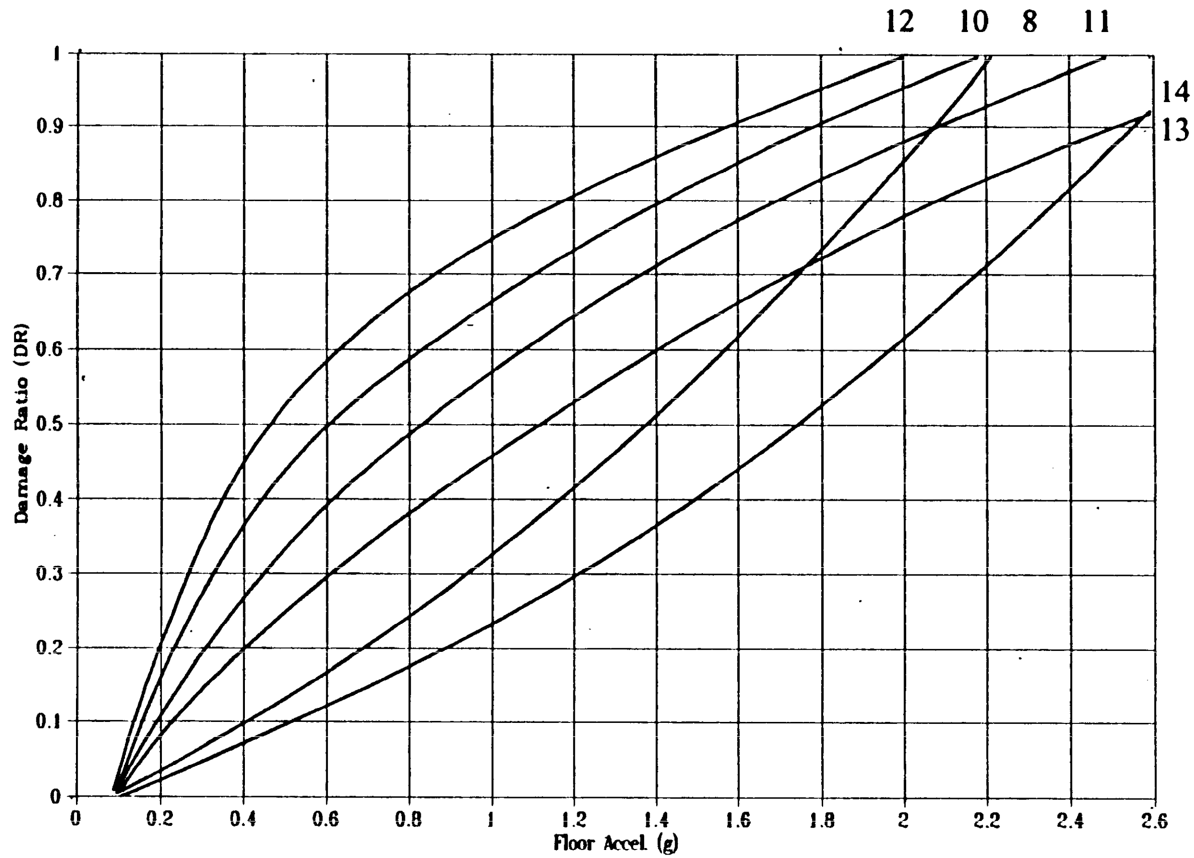
Figure 4. Continued.



5. Steel Moment Frames
4. Steel Braced Frames
2a. Steel Frames w/ CSW

3. Concrete Moment Frames
2b. Concrete Frames w/ CSW
CSW - Concrete Shear Walls

Figure 4. Continued.



13. Floor Finish & Roof
10. Partitions & Ceilings
11. Mechanical & Electrical
9. Architectural Glass
14. Elevators
8. Foundation and Site Work
12. Contents

Figure 4. Continued.

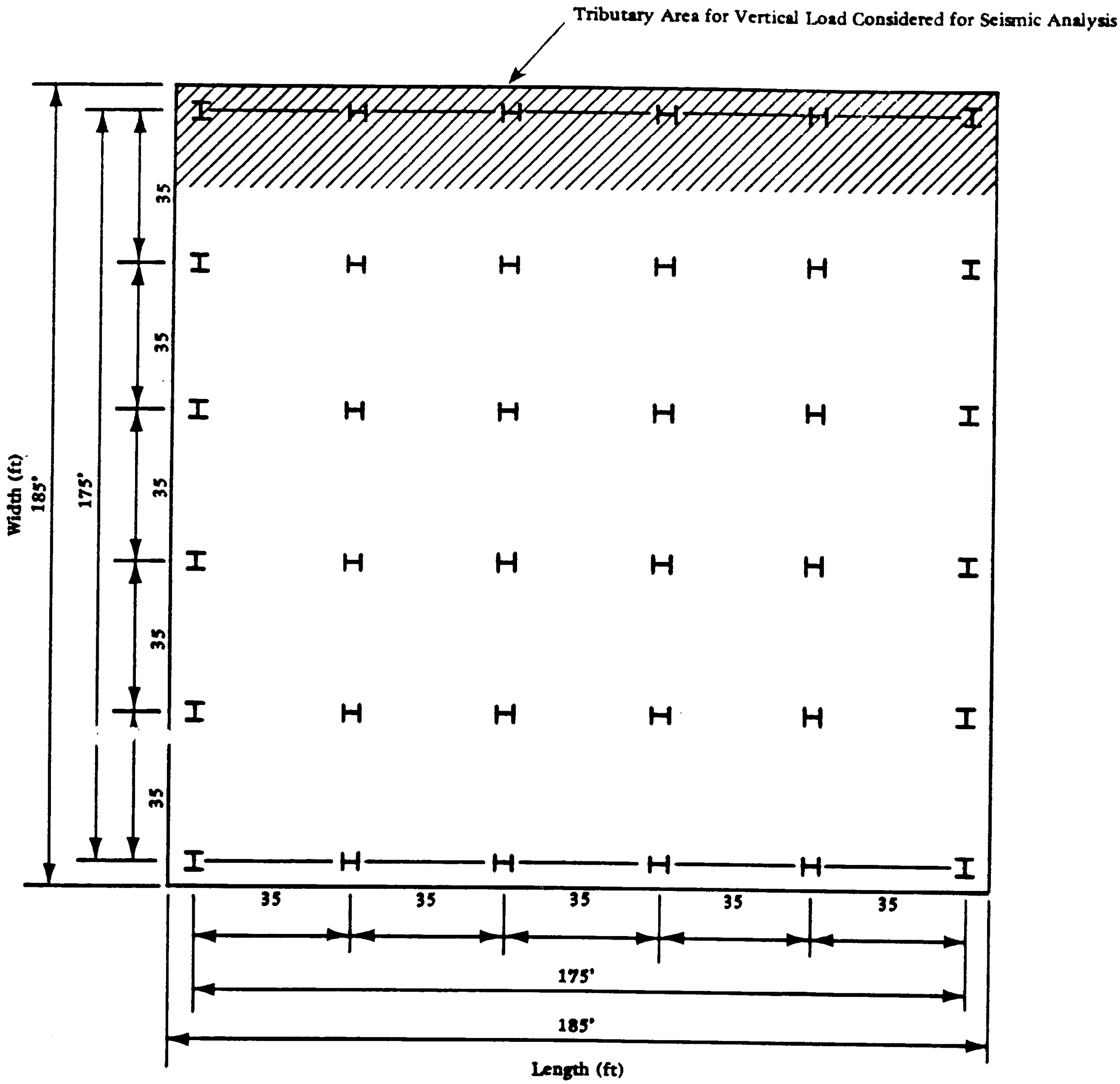
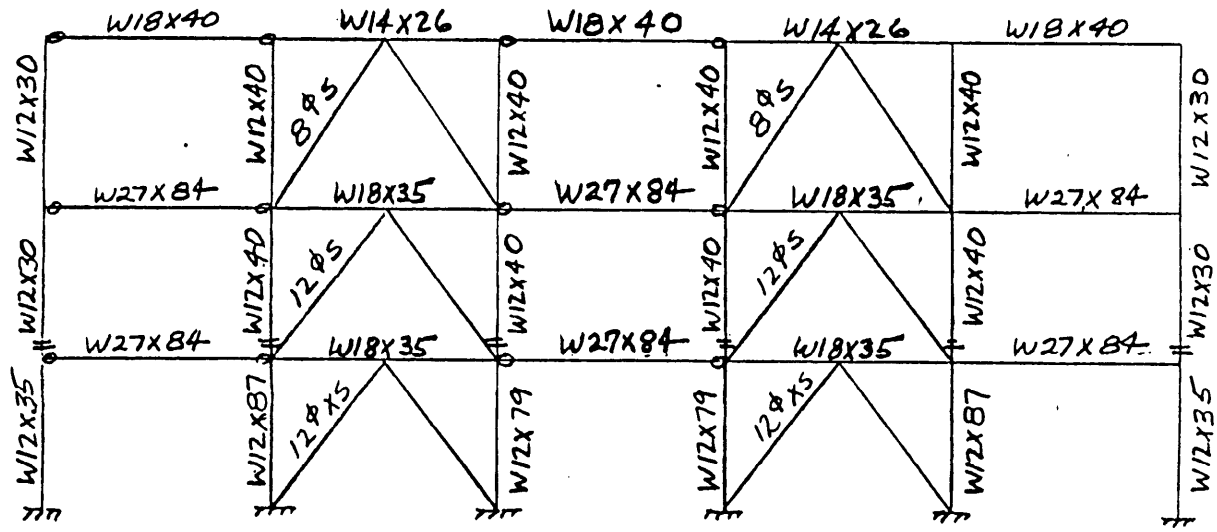
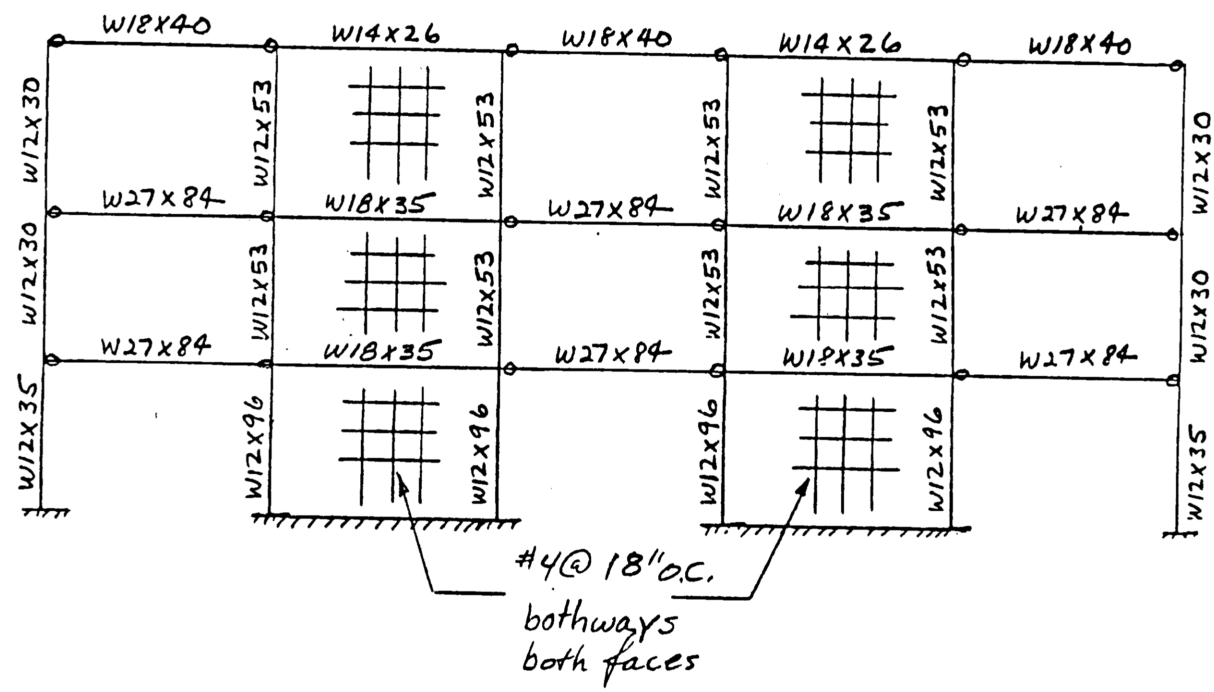


Figure 5a Example building plan view.

0.20 g elastic design, $\mu = 1.0$



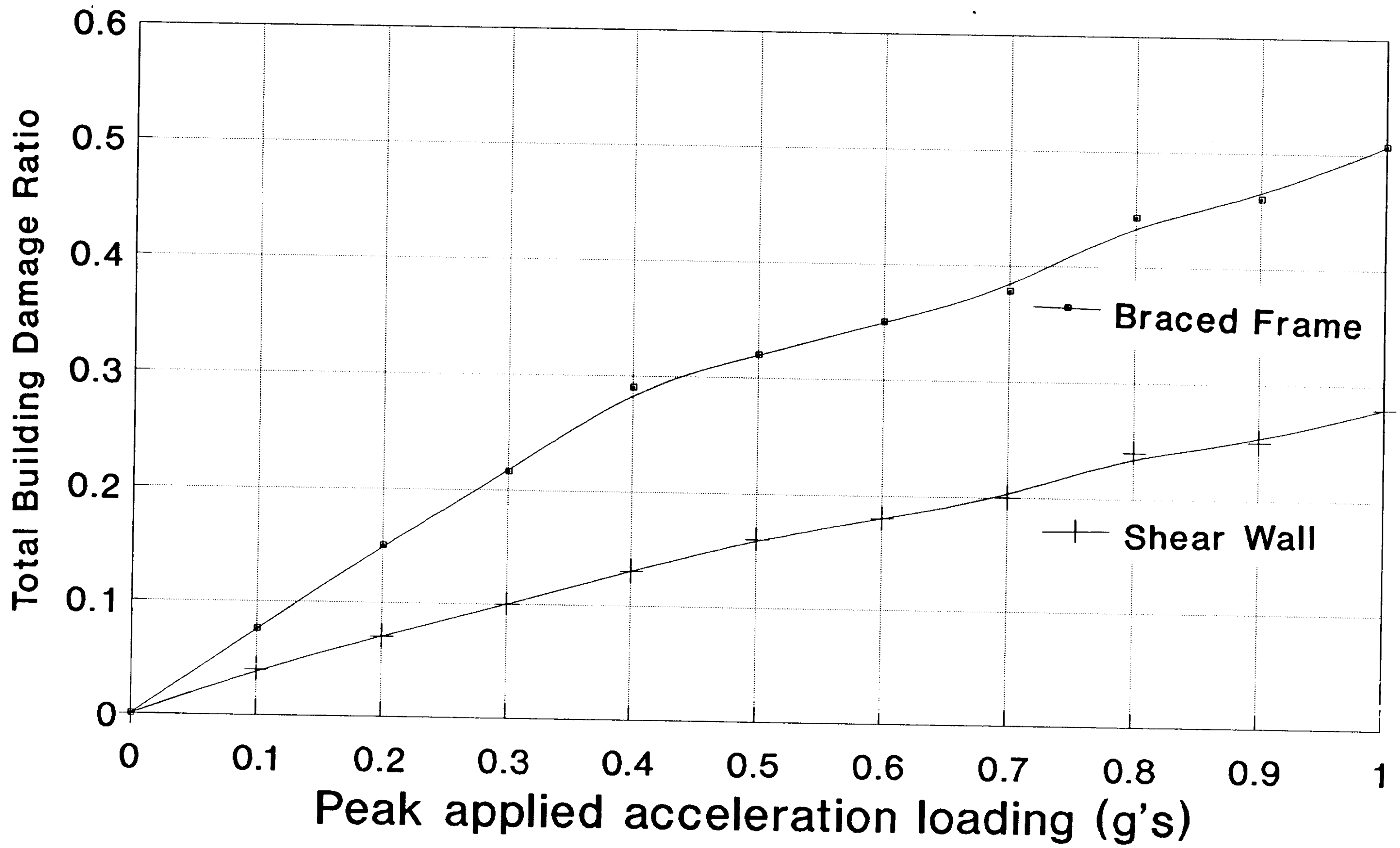
Braced Frame



Shear Wall

Figure 5b. Sections showing braced frame and shear wall alternatives.

Figure 6. Damage ratio for alternatives.



Proposed Criteria

for

Economic Analysis Of Seismic Design Alternatives

Seismic Exposure (Step 1)

Fundamental to evaluating the potential for seismic damage is quantifying of the hazard exposure. This is accomplished by a site seismicity study which determines the intensity and characteristics of ground motion shaking which pose a risk to a specific location. The method of performing a site seismicity study has become standard practice and is used by many geotechnical firms. In general, an historical epicenter data base is used in conjunction with available geologic data to compute the probability distribution of site ground motion. The process of quantifying the level of hazard involves building a mathematical model of the region. The seismic model must be based on the knowledge of the local area in sufficient detail to yield results appropriate to estimate site motion for events with return times on the order of 1,000 years. The results of a seismicity study are presented in an engineering report which gives a discussion of the results, the site acceleration probability distribution, and the determination of specific site acceleration levels to be used for building design.

The structural design engineer may use either a response spectra or earthquake time history in the analysis of a structure. The data base of available recorded accelerograms is routinely used to generate a series of spectra or time histories for use by the structural and geotechnical engineers in further assessment of the site.

Seismic Cost of Alternatives (Step 2)

When an economic analysis is applied to a design project considering alternative concepts, it is necessary to evaluate the cost of each alternative. A preliminary structural design must be performed to determine structural member sizes for each alternative. Additionally nonstructural items affected by the seismic forces must be designed to the extent that they represent significant cost factors which vary among the alternatives. For special structures such as base isolated buildings, special requirements such as building clearance, flexible utility connections, isolator design, etc. must be included to be able to define the structure. Once the structure is defined a detailed cost estimate can be completed. This is a very important step in the economic analysis and one which determines the level of accuracy. As is usual practice in preparing a cost estimate, the structure should be broken down into major components and the cost of each component noted separately. The division of the building into components is an important step since each component will be later analyzed for damage. As will be shown later, it is important to separate out components which are drift sensitive from those that are force/acceleration sensitive. Equipment mounted on floors will be sensitive to the acceleration levels it receives; while, items such as vertical plumbing risers spanning between floors will be drift sensitive. Some items will fall into both categories. As a minimum, the major components should include the structural system, non structural partitions, exterior walls, floors, foundations, ceiling lights and fixtures, mechanical equipment, electrical equipment, and building contents. Where desired, a component may be subdivided into elements for a more detailed evaluation. It is required that a detailed cost estimate be compiled for each

Performance Objective

Navy waterfront facilities fall into the category of essential construction. There is an increased emphasis on post-earthquake functionality of essential construction. In this light, it is important to be able to evaluate the extent and location of expected building damage. Are there any weak links in the building system design which will preclude operability? Operability demands that the building be viewed as a total system not just a structural system. Utilities and the other elements must function to have operability. Additionally a procedure is required to evaluate alternative seismic designs and select the most effective choice. This guidance presents a detailed analysis procedure which can evaluate seismic strengthening, expected damage and the economics of seismic design for a building system.

The purpose of this procedure is to perform an economic comparison of alternative designs of a structure considering initial construction expenditures and expected earthquake induced damage over the life of the structure. It may compare different types of construction or different design levels. It is thus intended to assist the user and the design engineer in obtaining cost effective seismic construction. The Navy seismic economic analysis procedure is a process of estimating earthquake damage based on both interstory drift (displacement) and floor acceleration. As such it recognizes that the building system is composed of components, some structural, some nonstructural and some mechanical and electrical, which are affected by displacement or drift. It also recognizes that damage is induced in some building system components which are mounted to floors or ceilings by the transmitted story accelerations. The procedure of including both drift and acceleration is a significant factor in this procedure which is an improvement over other techniques which focused only on drift. Failure to include the acceleration induced damage leads to erroneous conclusions that mere stiffening which reduces drift is fully effective. For every dollar that is invested in stiffening a structure, a portion of it may be wasted because stiffening results in increased floor accelerations which can cause additional damage to acceleration sensitive components like contents.

This criteria defines the steps in the procedure for conducting an economic analysis. The initial step is to establish the seismic exposure of the building site. The building is divided into components based on function and damage mechanism Some components are drift sensitive while others are acceleration/force sensitive. The cost of building components must be identified to distinguish variations in cost of alternatives. A series of analyses are conducted for the range of expected site ground motion for each alternative concept to determine interstory drift and floor acceleration. Damage functions are used to determine component damage. Since the damage can occur at any time over the life of the structure, the present value of the damage cost is determined. Loss-of-use costs may be included. Damage costs are combined with initial strengthening costs to determine total expected cost for comparison of alternatives.

alternative being evaluated. There may significant portions of the cost estimate which do not vary among the alternatives. The amount of work involved is not as great as it might appear. Once a routine detailed cost estimate is prepared for the basic structure concept, as is standard practice, only those elements which change among alternatives need be evaluated. Use of individual components has the added benefit of showing where the damage occurs and whether there are any weak links in the building system. This is especially important for buildings which are expected to remain operational after an earthquake.

Damage Evaluation (Step 3)

Earthquake induced structural damage is caused principally by two mechanisms: interstory drift and story forces/accelerations. Drift is the mechanism usually causing damage to structural systems. There have been numerous tests conducted of lateral structural resisting systems which show the strength of these elements under cyclic load reversal. Building elements anchored to floors or suspended from ceilings feel the floor acceleration and respond as substructures. Depending upon the natural period of the structure, floor accelerations can be significantly higher than surface ground motion levels and tend to increase with height within the structure. Damage relationships are shown in Figure 1.

For each alternative it is necessary to conduct a series of dynamic analyses to compute damage over a range of possible ground motion levels. Typically the distribution is broken into increment bins of 0.1 g size covering a range of 0 to 1.0 g for the particular site. A set of ten dynamic analyses starting at 0.05g to 0.95g would be appropriate to cover the range of possible accelerations which could produce expected damage of significance. For a specific alternative, a basic finite element model would be constructed; then, the ten analyses of the model would be performed in which the applied load level was increased from 0.05 g to 0.95g. The results of the analysis are used to establish the interstory drifts and floor accelerations at each applied load increment. These are used to compute the damage ratio for each component by using Figure 1, examining the individual component elements and their appropriate drift and/or floor acceleration. The damage evaluation process is repeated for each of the ten applied load levels from 0.05g to 0.95g for each alternative.

The element damage relationship expressed in Figure 1 is in terms of a damage ratio; the actual element damage cost is obtained by multiplying the damage ratio from Figure 1 times the element cost from the cost estimate. Alternatively the element damage can be summed to a component level based on average damage ratios and then expressed as a component damage cost based on the average damage ratio times the component cost. Experience has shown that the cost of repair is greater than the original cost because elements must first be removed before the damaged component can be repaired or replaced. A component repair multiplier, R, is used to account for this increase.

Lateral force resisting system	1.5
Other structural components	1.5
Mechanical equipment	1.25
Electrical equipment	1.25
Architectural elements	1.25
Elevators	1.25
Contents	1.05

The Total Building Damage for a given iteration of acceleration load level can be expressed as:

$$\text{Total Building Damage} = \Sigma \text{ (Damage Ratio) * (Component Cost)* (Component Repair Multiplier)}$$

Additional cost factors can be included in the Total Building Damage at this point, such as loss of life, injury and down time. Loss of functionality can be a very significant cost factor for certain types of facilities. It can be estimated in terms of lost revenue for income producing facilities or in terms of the work-force salaries for service facilities. The owner/user is willing to pay an aggregate salary to have a work-force perform a set of functions. The inclusion of these indirect costs are significant and can shape the results of an analysis. The users can in most cases express the loss of use of the structure and this information should be included.

The Expected Building Damage Cost is computed by multiplying the probability that the acceleration increment from the histogram will occur times the damage or damage ratio for the building evaluated at that acceleration increment, and summed over all acceleration loading increments. The Expected Building Damage Cost for the specific alternative concept over the range of possible accelerations is given by:

$$\text{Expected Building Damage} = \Sigma \text{ (Total Building Damage for increment “bin” of acceleration) * (Acceleration “bin” Probability)}$$

Since the damage will occur some time in the future it must be expressed in terms of the present value (PV) to relate it to the current costs of seismic strengthening or remediation.

$$\text{Current Expected Damage Costs} = \text{PV(Expected Building Damage Cost)}$$

The present worth can be determined by dividing the exposure time into segments and then taking the present value of each segment or more simply by using a single average exposure time equal to half the total exposure time.

The life cycle cost of this alternative is the sum of the initial construction cost plus the present value of the expected damage.

$$\text{Alternative Cost} = \text{Initial Construction Cost} + \text{PV(Expected Damage Costs)}$$

Engineers have used two forms of structural dynamic analysis: response spectra procedures and time history solutions. A nonlinear time history solution is preferred because it directly computes displacements and floor accelerations taking into account structure yielding. Since there is substantial variation among earthquake records even when scaled to the same nominal peak acceleration value, the selection of an acceleration record can be a factor in establishing the maximum response of the structure. The choice of records should be examined to quantify variation in response and a series of three acceleration time histories is typically used to cover a range of response. It is important to note that as the ratio of applied loading to design load increases, the structure undergoes increased deformation and possible nonlinear behavior. As the level of deformation increases, an increase in damping occurs which must be included in the analysis. Care must be taken at each load level iteration to select the appropriate damping for that load increment.

Simplification of General Approach

The above procedure involves three main steps: the quantification of the seismic hazard in probabilistic terms, the determination of the initial costs of seismic strengthening or remediation, and the determination of the expected damage. An incremental approach is used in which the ground motion acceleration probability distribution is expressed as a histogram composed of incremental “bins” of acceleration and their associated probabilities of occurrence. This produces a full and complete analysis of the best estimate of the seismic exposure. However, a site seismicity study may not always be available. The engineer is free to substitute a set of earthquake events of design interest. This set is not a complete risk assessment but rather is a comparison of the proposed structural design alternatives under an assigned set of design load conditions. Having done this, the designer may choose to consider the average performance of the structure under the assigned set of events, or perhaps the worst case event, or perhaps the cumulative effect of all the events. Again it is important to note that this approach is not a total risk analysis but only a relative comparative performance of the alternatives under a set of design conditions. It was suggested that nonlinear time history finite element models of the structure be used to estimate drift and floor accelerations using sets of time histories. The engineer may substitute elastic response spectra techniques if he chooses as long as the results are adjusted for yielding.

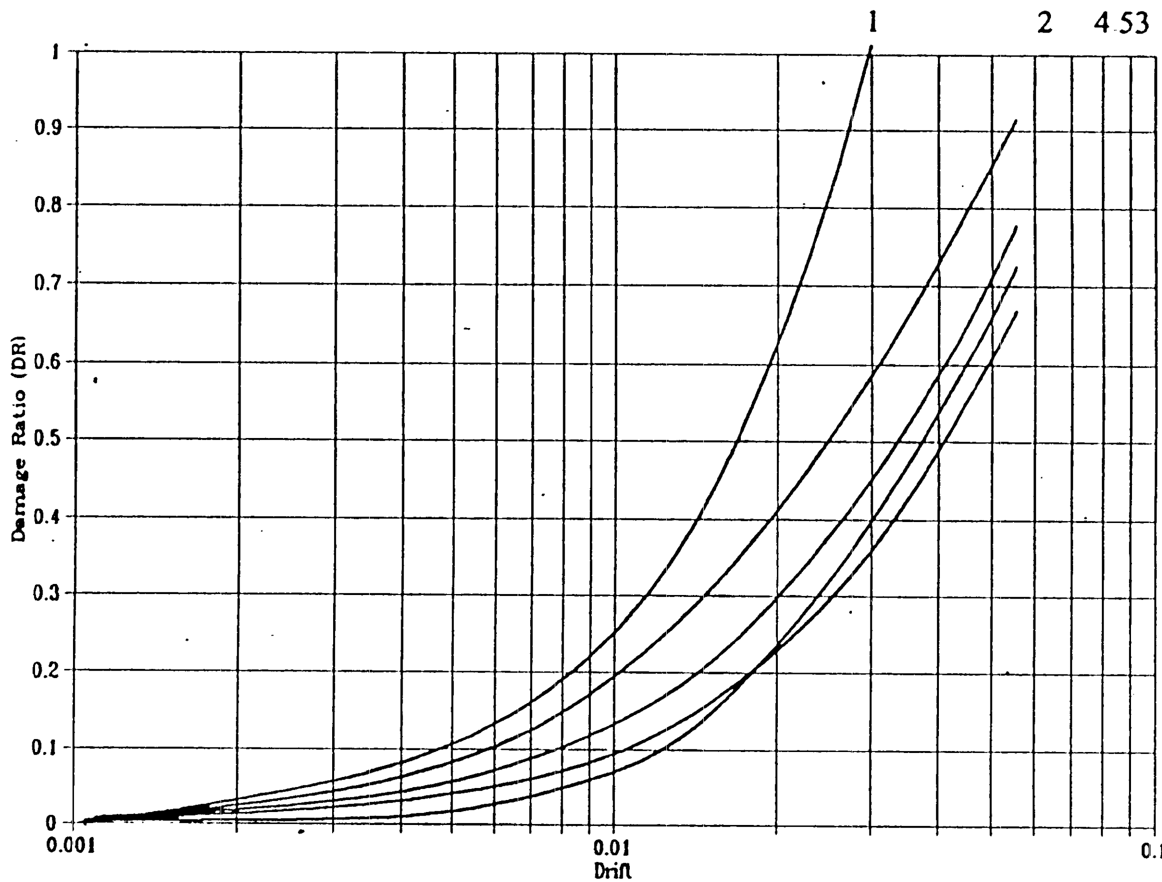


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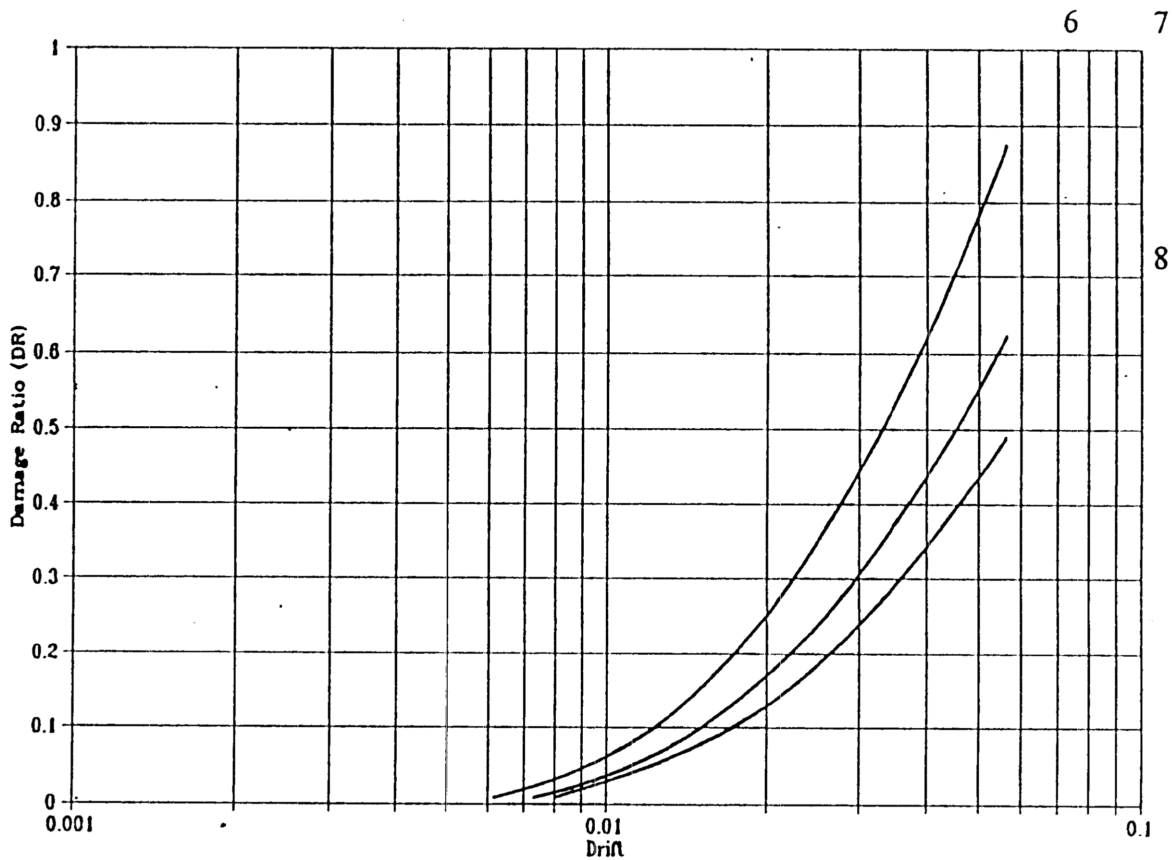
Figure 1. Damage as a function of drift and acceleration. (based on Way (1995))



6. Structural Frames
7. Structural Floors
8. Foundations

Figure 1. Continued.

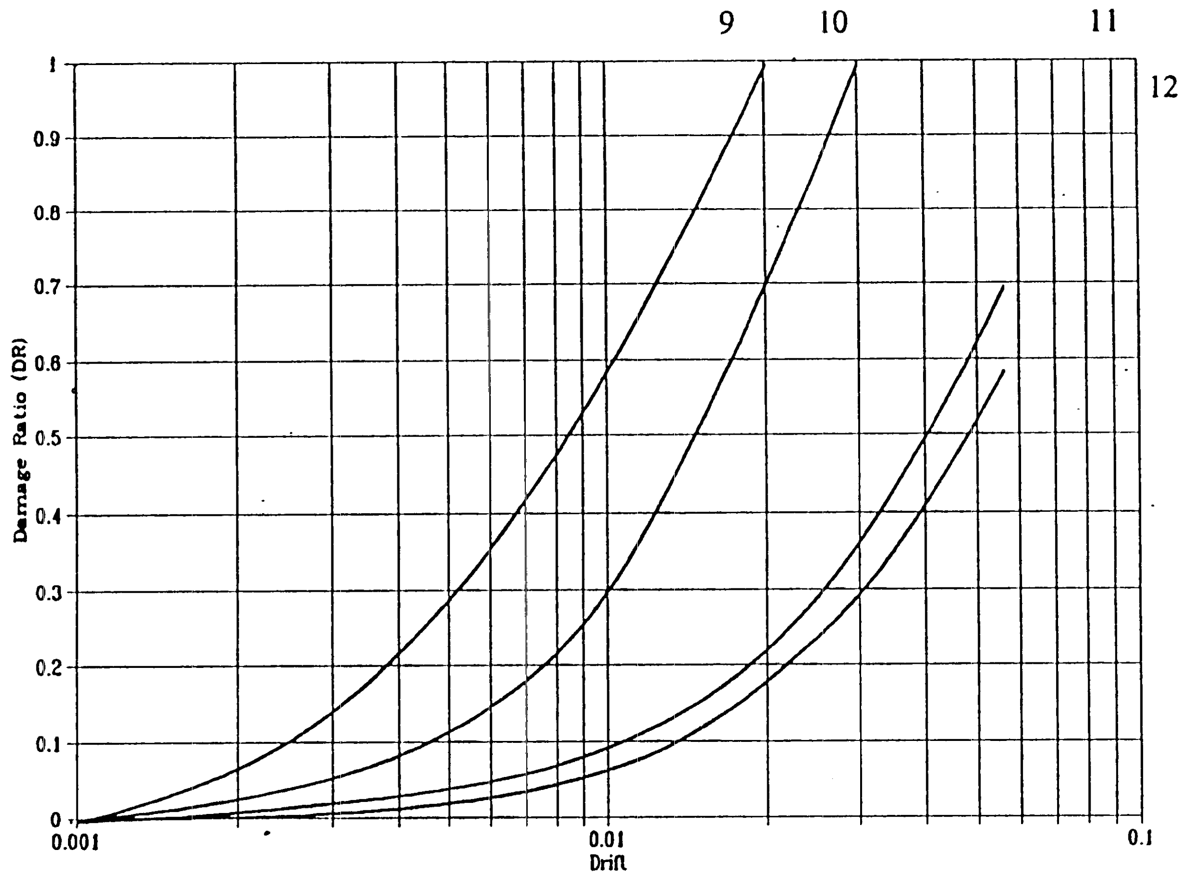


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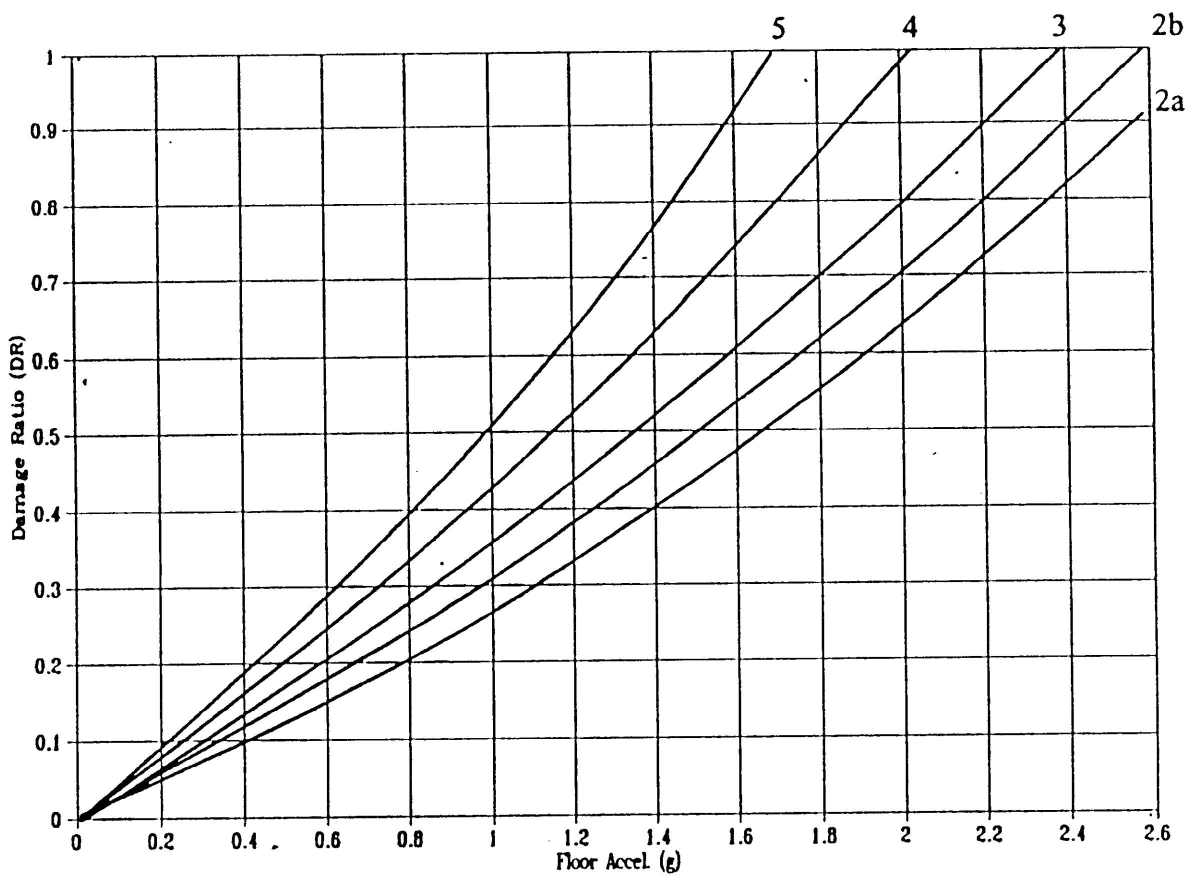
Figure 1. Continued.



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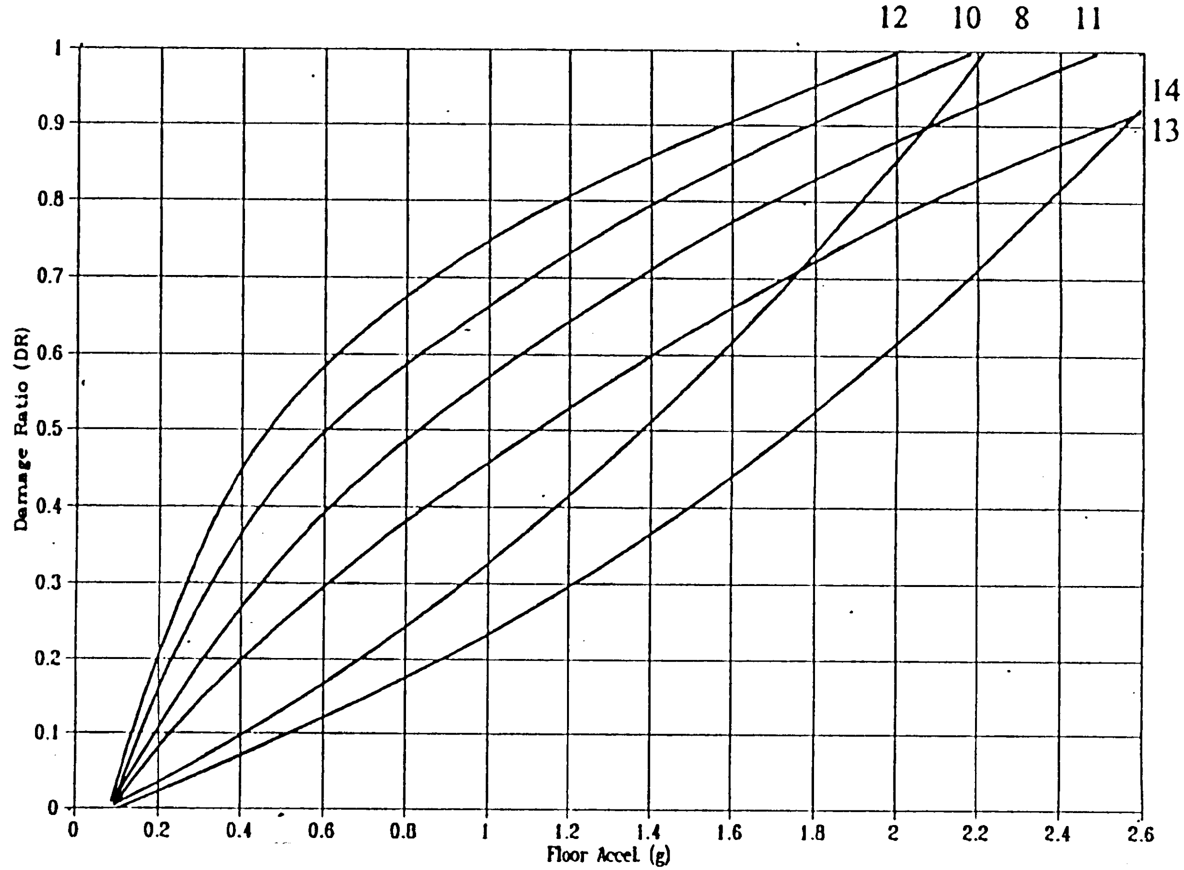

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Figure 1. Continued.

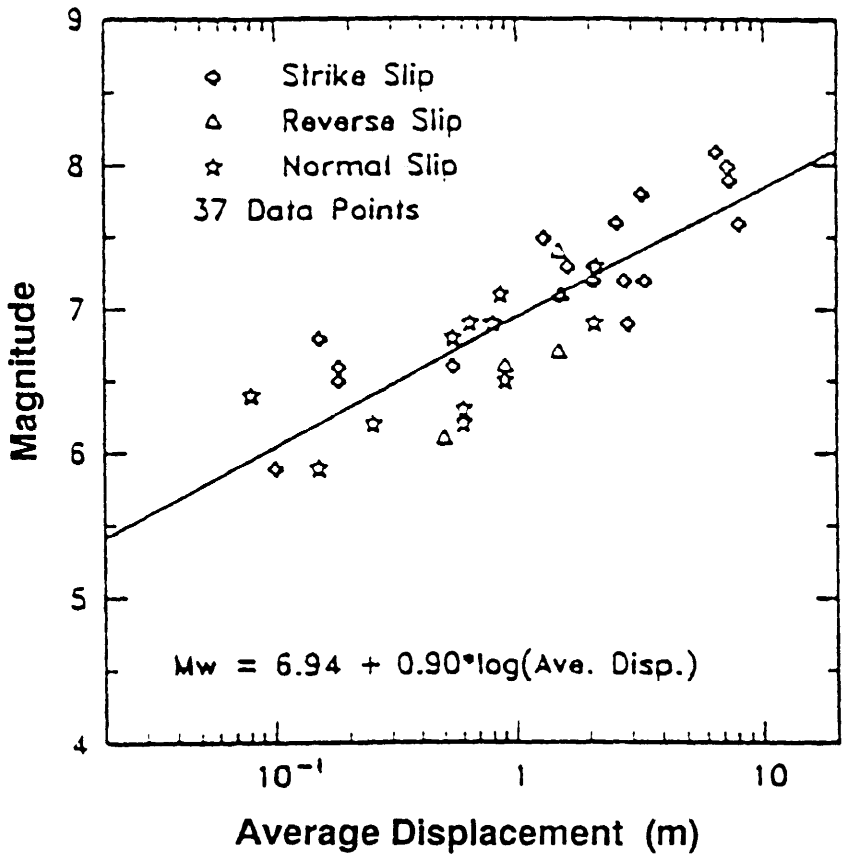

Figure 1. Earthquake Magnitude versus average surface displacement (from Coppersmith, Proceedings Fourth International Conference on Seismic Zonation, 1991)

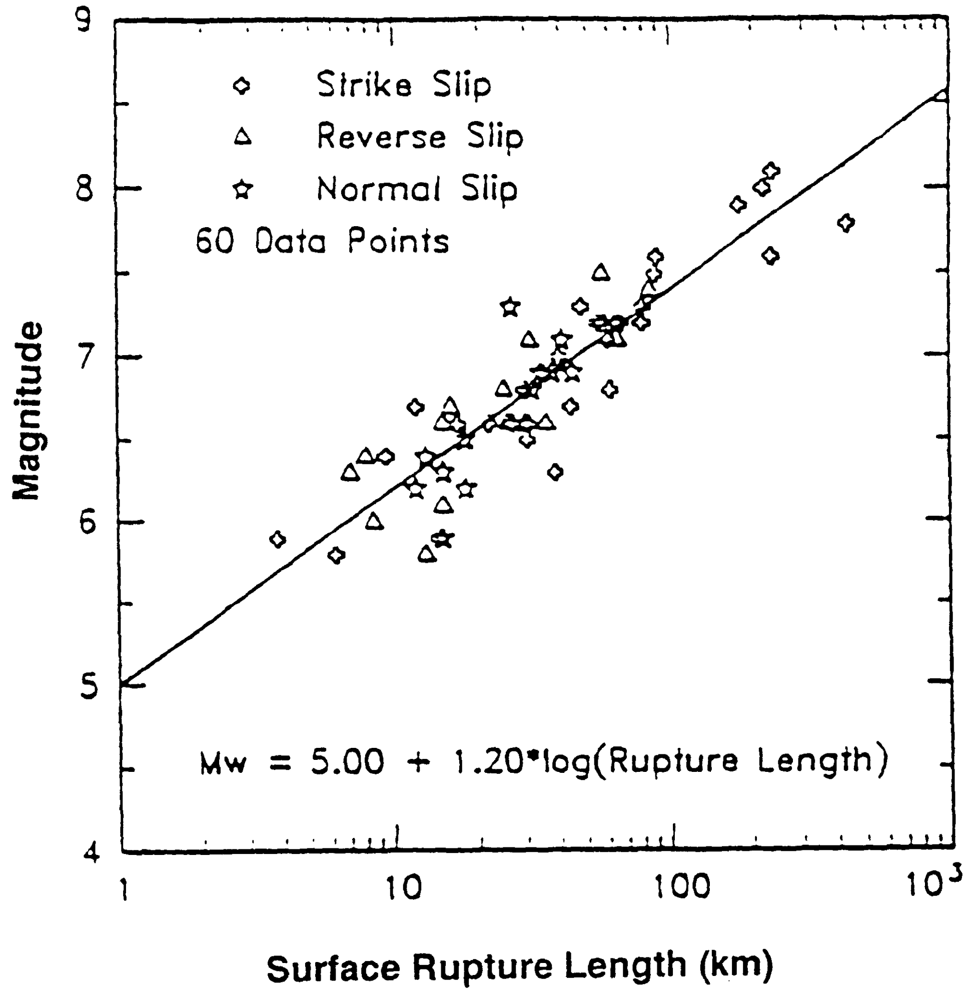

Figure 2. Earthquake magnitude versus fault surface rupture length. (from Coppersmith, Proceedings Fourth International Conference on Seismic Zonation, 1991)

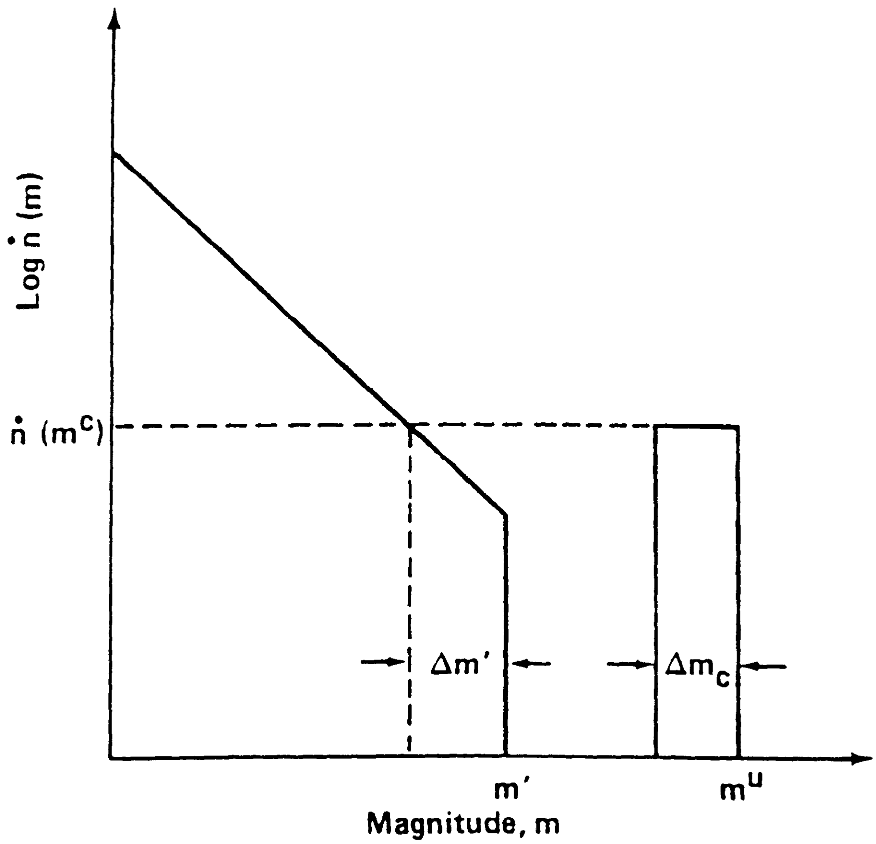

Figure 3. Generalized frequency magnitude density function.

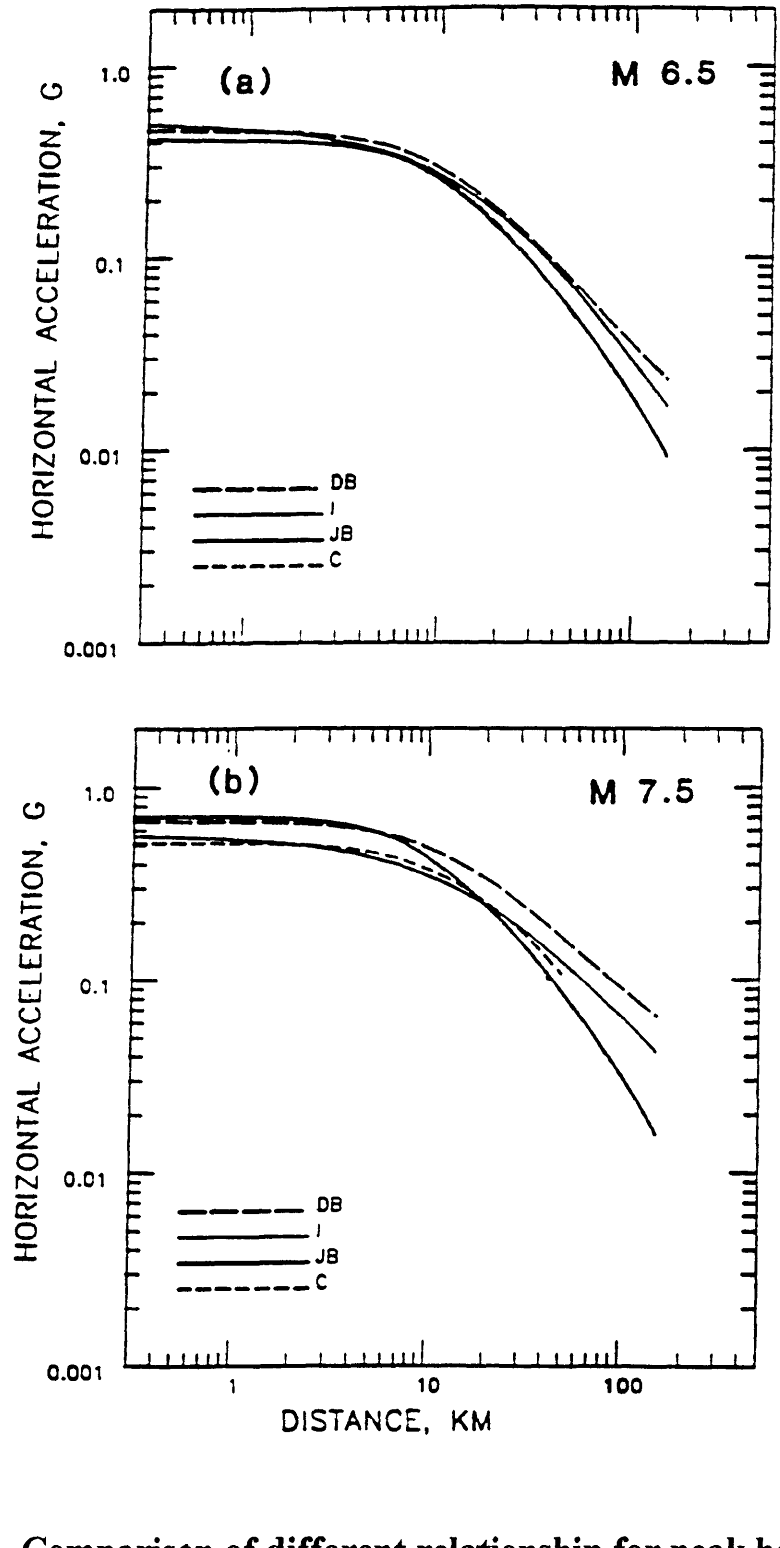

Figure 4. Comparison of different relationship for peak horizontal acceleration at Magnitude 6.5 and 7.5
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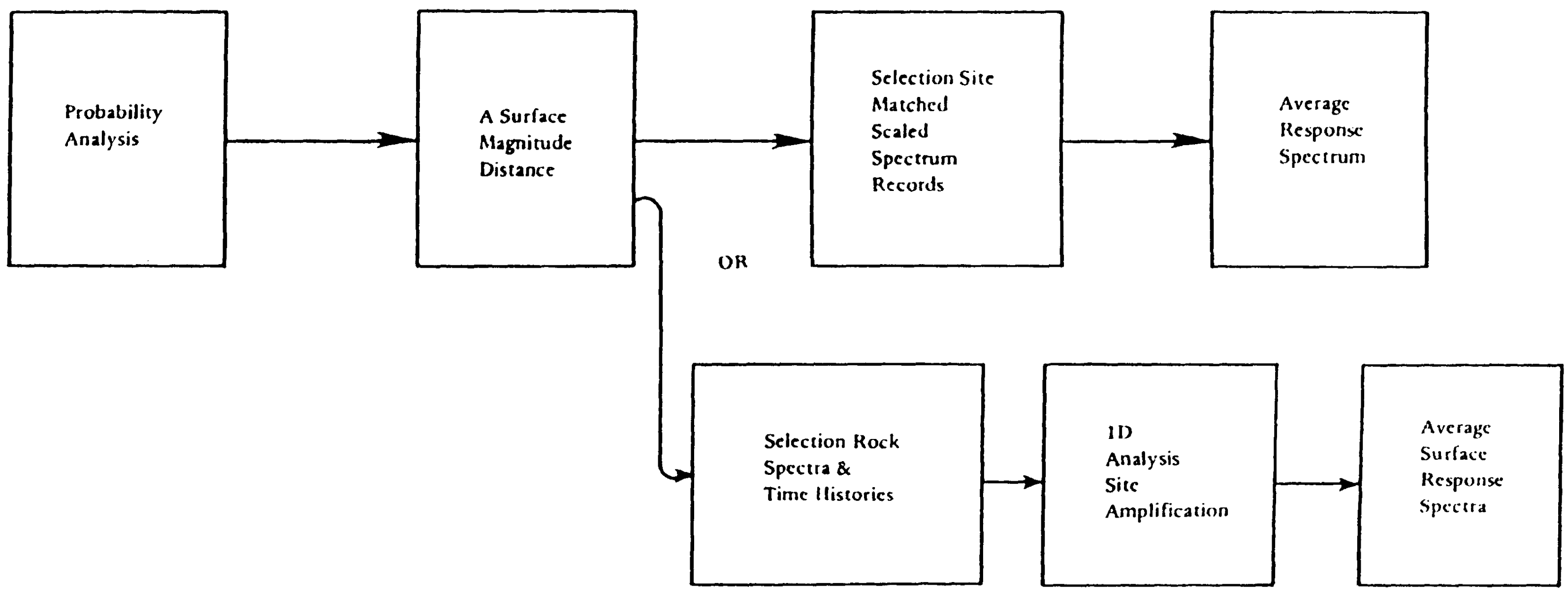

Figure 5. Flow chart of analysis